Geophys. J. R. astr. Soc. (1978) 53, 373–412

Palaeomagnetic record of a late Tertiary field reversal

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Received 1977 October 12; in original form 1976 December 29

Summary. A palaeomagnetic record of a field reversal has been obtained from the Tatoosh intrusion in Mount Rainier National Park (latitude 46° 50′ N, longitude 121° 45′ W). The VGP before and after the reversal is conformable with the North American polar wander curve. The reversal in direction is preceded by a decrease in intensity of the NRM of more than an order of magnitude. Immediately prior to the reversal the dispersion of the directions of magnetization increases. The reversal in direction is accomplished by a convoluted VGP path which traverses the Pacific and is somewhat confined in longitude. Subsequent to the completion of the change in direction the field intensity recovers, so that the intensity change takes at least twice as long as the directional change.

The definition of the reversal plane in the Tatoosh intrusion gives the orientation of the cooling front at the time the reversal took place. An analysis of the cooling history of the body, in conjunction with the magnetic results, suggests that the body did not cool by simple conduction, and that convective heat transfer by meteoric water is important. This defines a two-stage cooling of the margin. At high temperature rapid cooling takes place as the water chills the hot rock. Later the circulating water in the cracked permeable margin maintains a moderate temperature for long periods.

Long vertical cores from the intrusion have revealed a palaeomagnetic record similar to present secular variation records and suggests that some tens of metres of core from intrusive similar to the Tatoosh could give important resolution records of the geomagnetic field.

A second reversal record was obtained from the Laurel Hill intrusion near Mount Hood, Oregon (latitude 45° 20′ N, longitude 121° 4′ W) which is approximately 10 Myr younger. The smoothed VGP paths for the two reversals are essentially identical. Other $R \rightarrow N$ paths from North America appear to favour the Pacific, although the Lake Tecopa record of the last reversal is a notable exception. In comparing all available reversal paths, one finds that although individual paths are confined in longitude, no longitude is uniquely preferred nor does the site uniquely determine a path longitude. There is some preference amongst $R \rightarrow N$ paths to favour the Pacific and the $N \rightarrow R$ the Euroasian landmass, but the limited distribution of observation sites precludes a satisfactory distinction between site control or absolute control in geographical coordinates.

Dominantly quadrupolar transitional fields are consistent with the records. Such fields are predicted by a variant of the Steenbeck Krause α^2 DC dynamo, but $\alpha\omega$ dynamos may also exhibit quadrupolar transitional fields as indeed does the Sun. Some stationary non-axisymmetric component is required to explain non-zero declination of the observed transitional fields.

1 Introduction

The demonstration that the age and polarity of magnetization of lavas could be used to give a world wide reversal chronology for the last four million years established the reality of field reversals (Cox, Doell & Dayrymple 1964; McDougal & Tarling 1964). Subsequently, the palaeomagnetism of ocean sediments (e.g. Opdyke 1972) was found to be consistent with the time scale of reversals observed with the lavas. Finally, the ocean floor magnetic anomalies were used to extend the reversal record back to approximately 100 Myr (Heirtzler *et al.* 1968). With the establishment of the chronology of reversals recent studies of reversals have concentrated on details of the frequency of their occurrence and the nature of the transitional fields. The subject of reversals was comprehensively reviewed nearly ten years ago by Bullard (1968) and more recently by Jacobs (1976).

The distribution function of lengths of the most recent polarity intervals has been discussed by Cox (1969) and Nagata (1969). In Cox's initial analysis, the geomagnetic dynamo was assumed to exhibit simple harmonic oscillation about a fixed value and to reverse when triggered by random fluctuations of the more rapidly varying non-dipole field. He then showed that the lengths of polarity intervals follow a Poisson distribution so that the probability of a reversal in time dT is

$$f(T) = \lambda \exp(-\lambda T) dT$$

where $\lambda = P/T_D$, with P as the probability of a reversal during one dipole cycle of length T_D. T_D was taken to be 7×10^3 yr. From this analysis a good fit to the data for $0.02 < T < 3.32$ was obtained with P equal to 0.055. Fitting the ocean floor anomaly data for the past 10.6 Myr gave $P = 0.043$. Cox concluded that on the average 20 fluctuations of dipole intensity should take place before a reversal. Turning to more remote geological times, one finds evidence that very different reversal rates have occurred for substantial periods of time (McElhinny 1971). For example, during the Permian the field exhibited a predominantly reverse polarity for a period of some 20 Myr. This observation led to the suggestion that the average rate of reversals may be related to core–mantle boundary conditions and that it changes only over long periods of geological time, but that individual reversals are related essentially to random processes in the fluid core (e.g. Cox 1969). Emphasis is now being placed on detailed analyses of reversal rates to see if there is any structure which might be related to core processes of field generation (Naidu 1971; Cox 1975).

Many attempts have been made to observe the transitional fields, which occur during a geomagnetic field reversal, to see if sufficiently distinctive behaviour may be found to establish some particular aspect of the geomagnetic dynamo. The studies of ocean sediments have been helpful in establishing the time taken for the reversal. Harrison & Somayajulu (1966) used a high deposition rate core to obtain an estimate of 4000 yr for the change in direction during a reversal. More recent work by Opdyke, Kent & Lowrie (1973) gave similar estimates of 4600 yr for the lower Jaramillo transition. These latter workers suggest that the directional change and the associated intensity fluctuation take comparable time.

In general it is difficult to obtain records from different parts of the world for a single reversal. Indeed for any but the most recent reversals, inaccuracies in age determination may preclude the demonstration that one is looking at the same reversal. Nevertheless, studies of the last reversal have given this important type of data. In comparing different reversal records it has become customary to compare the VGP paths, by which the reversal of the fields is accomplished. We will follow this custom. However, it should be recognized that the interpretation of VGP paths is not straightforward, since there is no guarantee that the field is actually dipolar. Niitsuma (1971) reported a VGP path for the last reversal from a study of Japanese sediments, which was confined in longitude and centred on a meridian passing through Japan. A Euroasian path was found by Koci (1973). In contrast Kawai *et al.* (1973), using a Pacific core, reported a path traversing the eastern Pacific and Hillhouse & Cox (1976) reported a VGP path from the Lake Tecopa sediments, which traversed the Atlantic. Hillhouse & Cox (1976) concluded from comparing their result with that of Niitsuma (1971) that the field could not be dipolar during the reversal. Recently Freed (1977) has reported paths observed in oceanic sediments for the Panama basin, which are similar to those recorded by Hillhouse & Cox (1976).

Some remarkable records of earlier reversals have been obtained with continental sediments. Russian workers (Kaporovich *et al.* 1966; Gurary 1973; Burakov *et al.* 1976) were able to observe the Gauss/Matuyama reversal in several sections over a distance of several hundred kilometres and to demonstrate that the VGP paths were similar for all sites. These authors describe a longer time scale for the reversal than is commonly accepted. They, like Momose (1963) consider that reversals in direction may take as long as 10^5 yr. However, such times are not consistent with the magnetostratigraphy of the continental lavas, of the ocean sediments, nor with the seafloor anomalies. The Russian authors were able to classify reversals into groups on the basis of the characteristics of the VGP paths. Baag & Helsley (1974) studied Triassic reversals in the Moenkopi formation and found that common paths were exhibited for different reversals.

One of the earliest records to be obtained was from the Stormberg velocities in Africa (Van Zijl, Graham & Hales 1962a). Records from lavas are particularly useful for estimates of the intensity of the field during reversals, but the detailed chronology of the process is hard to obtain because it depends upon the extrusion rate which is generally unknown. Nevertheless, very interesting records have been described by Watkins (1969) and Larson, Watson & Jennings (1971) from sections of lavas in southeast Oregon and northwest Nevada. These again showed confined VGP paths, even though lavas cool in times short compared with the secular variation and so record effectively spot readings of the field. In contrast records from intrusions (Dunn *et al.* 1971) give time averaged changes in the field. An advantage of the intrusion records is that they are likely to be truly continuous records since the motion of the cooling front into the body is continuous and it controls the acquisition of NRM. A disadvantage is that one does not know the absolute time involved in the record as it depends upon the cooling time of the intrusion which is not usually accurately known.

Several reviews of the observed transitional regimes of the geomagnetic field have appeared (Creer & Ispir 1970; Dagley & Lawley 1974; Cox, Hillhouse & Fuller 1975; Petrova *et al.* 1972; Steinhauser & Vincenz 1973). The main features of the reversal process are reduction of the field strength and an increase of the dispersion in direction of magnetization including swinging of the field. The reversal of polarity is achieved with a VGP path which is usually somewhat confined in longitude. In addition to these features, upon which there is general agreement, there are more controversial suggestions such as that of Creer & Ispir (1970), who claim that the VGP paths for recent reversals define preferred longitude zones. In his recent paper, Hoffman (1977) sheds important light on the problem of VGP paths by pointing out the dependence of the path upon the site location given certain models of field reversal. He notes that earlier workers have ignored the fact that if the transition field is axisymmetric VGP paths will be confined to longitude. There is some dispute as to whether the intensity decrease is simultaneous with the directional change (e.g. Opdyke *et al.* 1973) or whether the intensity change is longer than the directional change (Dunn *et al.* 1971). Unfortunately, the number and the nature of available reversal records make generalizations concerning the details of field behaviour during reversals still somewhat hazardous.

In addition to true reversals, palaeomagnetism has revealed excursions of the field which may be related to reversals (e.g. Cox *et al.* 1975). Despite intense efforts to study such phenomena in lake sediments (Creer *et al.* 1971; Kawai *et al.* 1972; Dodson, Fuller & Kean 1976) the situation remains unclear, so that in a recent review Verosub & Banerjee (1977) state that they do not feel that 'the existence of any proposed excursion is yet significantly well established for its reality to be beyond question'. This may however be too pessimistic a view; there may very well be a variety of phenomena between true reversals separated by periods of constant polarity long compared with the time taken to reverse, through short reversals separated by times comparable for the reversal time, to local and perhaps incomplete reversals or excursions of the field due to non-dipole anomalies at times of low intensity of the dipole field (Harrison & Ramirez 1975). In view of the confused state of our understanding of these phenomena, we cannot yet learn much to help our interpretation of true reversals. However, the VGP paths for short reversals and excursions and the relation between intensity and direction changes may eventually be of importance.

Models of field reversals may be conveniently considered in two groups. First, there are models relying essentially upon analysis of mechanical analogues of the core dynamo process and second, there are models more directly related to postulated fluid flow processes in the core of the Earth.

An important recent advance in the analysis of the mechanical analogues has been made by Robbins (1976), who has re-investigated the Bullard disc dynamo and shown that it, like the Rikitake two disc version of the dynamo, can give short period field oscillations and reversals. Hence it is analogous to an AC reversing dynamo of the $\alpha\omega$ type.

Models of reversals based more closely upon the postulated core processes take as starting points, either the Bullard–Gellman–Lilley dynamo (e.g. Lilley 1970), or the Parker Cyclone model. Nagata (1969) suggested that the frequency of reversals (Cox 1969) can be reconciled with the Bullard–Gellman–Lilley dynamo, if it is assumed that on loss of the asymmetric Braginsky flow criterion, the field collapses, and that on recovery it has equal probability of being of the same or of reversed polarity. Parker (1969) has suggested a mechanism which is an extension of his earlier ideas of models to sustain steady dynamos. He notes, and has been followed by Levy (1971, 1972), that in high latitudes cyclonic motion can generate a toroidal field of opposite sense to that at lower latitudes from which the poloidal field is generated by the α process. Hence negative phase feedback is generated which destroys the normal field. Hoffman (1977) has noted that this Parker–Levy approach is broadly consistent with the observed $R \rightarrow N$ reversal records. Following the analogy of the reversal of the Bullard disc dynamo, Robbins (1976) argues that the reversal is an intrinsic property of the large scale hydromagnetic processes which maintain the geomagnetic field. Locally intense fields can bring about changes in the sign of the spatial gradients of the rotation. Hence reverse toroidal field can be generated. This in turn gives reverse poloidal field. Thus this model invokes a reversal of the toroidal field giving rise to reverse poloidal field, in contrast to the Parker–Levy approach which assumes reversal by the α process initially.

Finally, there have been a number of discussions of the reversal process which take as a starting point the palaeomagnetic data and try to develop explanations of them. As we noted earlier, Cox (1969) suggested that the geomagnetic dipole is a harmonic oscillator and that reversals are somehow triggered by the non-dipole field at the time of a minimum in the dipole field intensity. Creer & Ispir (1970) proposed that during reversals different offset dipoles reverse with different time constants, thus determining certain preferred VGP paths. These dipoles are tied to particular motions in the core (Bochev 1969). Verosub (1975) considers that the geomagnetic field may actually be due to the difference between two oppositely directed dipoles. When these dipoles are of equal strength the field reverses. Verosub (1975) suggested that one dipole has its origin in commonly accepted dynamo mechanisms taking place in the outer core. The other comes from processes in the solid inner core which are obscure. If one disregards the unorthodox notion that one of the dipoles is located in the inner core and instead places both dipoles in the outer core, this approach gives quadrupolar transitional fields.

There are then a considerable number of reversal mechanisms which have already been proposed and some of them make palaeomagnetically testable predictions given good enough records. In this paper, we describe attempts to obtain the necessary high resolution records from intrusions. The advantage of using intrusions is that as the body cools the range of blocking temperatures in which NRM is acquired sweeps continuously and at reasonably uniform velocity into the intrusions. It is therefore possible that records from intrusions could provide detailed information about reversals and give the secular variation during periods of uniform polarity. The NRM of the Tatoosh intrusion was studied in considerable detail because intrusions have sometimes been considered palaeomagnetically unreliable (Stordevedt 1968; Merrill & Grommé 1969). This analysis of the NRM and the origin of the magnetic phases in the Tatoosh intrusion have been described previously (Wu *et al.* 1974) and will be only reviewed as necessary in this paper. Under certain circumstances, the NRM of intrusions appears to be a remarkably reliable palaeomagnetic recorder.

2 Tatoosh intrusion – geology

A satisfying interpretation of the palaeomagnetic record of an intrusion requires an understanding of the geological history of the body and of the nature of the magnetic phases which carry the record. Unfortunately the details of the cooling history of an intrusive body such as the Tatoosh and the attendant paragenesis of the relevant mineral phases are hard to establish. There are still important aspects which we have been unable to settle unequivocably, but good palaeomagnetic records may eventually help to unravel some of the geological problems associated with the intrusions.

2.1 GEOLOGY

The Tatoosh intrusion is exposed in and around Mount Rainier National Park in the Cascade Mountains of the Pacific northwest of the USA (latitude 46° 50′N, longitude 121° 45′W). It is part of a volcanic and plutonic complex found in Eocene and Oligocene volcanics of oceanic origin (Fiske, Hopson & Waters 1963; Mattinson 1977). The earliest activity gave rise to a sill complex at about 26 Myr before present. This and the subsequent activity have been dated and described in considerable detail by Mattinson (1977). According to this work, the main plutonic core was intruded in two stages at 17.5 and 14.1 Myr. Our work has been confined to the southern mass which is part of the earlier intrusive stage. K/Ar dates of 18.05 ± 0.45 for a hornblende separate and 16.23 ± 0.13 for biotite were obtained by Bikerman (private communication). These dates are broadly consistent with those of Mattinson (1977), who used U^{238}/Pb^{206}. Earlier work reported by Fiske *et al.* (1963) gave a K/Ar age of 14.1 ± 1 Myr for samples from near to Nisqually bridge. If we discount the early

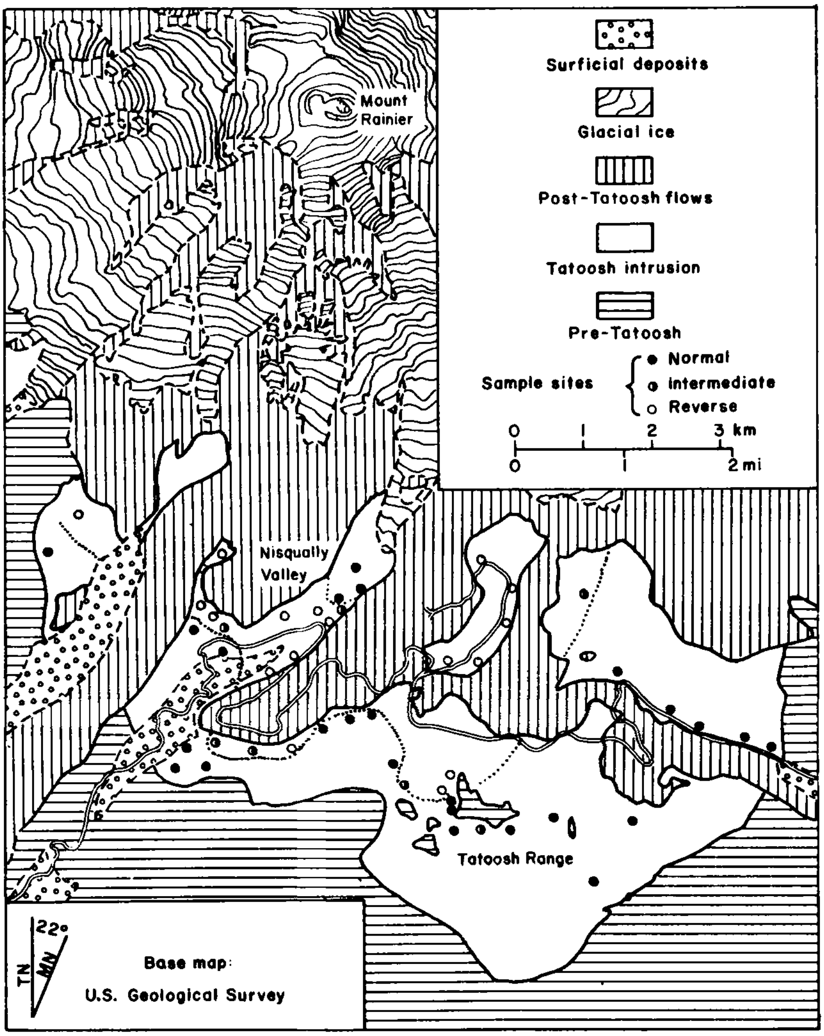

Figure 1. Map of southern mass of Tatoosh intrusion showing polarity zones.

K/Ar age it seems likely that the acquisition of NRM, and hence the reversal age, should have been between 17 and 18 Myr. This corresponds to blocking of magnetization somewhat later than the U/Pb closure and between that of the biotite and hornblende K/Ar closure. In view of the uncertainties involved in this age determination, it would not be wise to attempt to correlate this reversal with any other, but it is reasonable to distinguish it from reversals dated several million years younger or older.

Field studies (Fiske *et al.* 1964) reveal that the southern mass of the intrusion actually broke surface to give flows, so that it is clear that this is a very shallow intrusion. Initially, we collected as uniformly as was practical so that we might locate a suitable region to observe the reversal record. The results of this initial collection are shown in Fig. 1, and led us to concentrate our efforts in the Nisqually Valley section where a reversal appeared to be recorded and where the rocks were conveniently exposed. It is with this part of the Tatoosh complex we will be primarily concerned in this paper.

The geometry of the older plutonic phase of which Nisqually Valley is a part, is not well known. However, in some areas such as in the southwest we see an almost vertical steep contact. To the east and south, we see evidence of the roof of the body. Hence, we can be sure that we are fairly near the top of the body.

A petrographic study of the Tatoosh intrusive body in Nisqually Valley shows that the texture and mineralogical composition are rather homogeneous. The opaques are found to occur in association with felspars as well as with ferromagnesian minerals. The size of the opaques in biotite and hornblende is much larger than that of those in plagioclase. The main size peak for opaques in the felsic minerals is around 10 microns. The size distribution of opaques with maximum dimension smaller than 2 microns is not available at the present. However, electronmicroscopy has demonstrated the existence of particles smaller than 0.5 microns.

Qualitative identification of opaque inclusions in plagioclase by scanning electron microscopy coupled with X-ray fluorescence spectrometry analysis indicates that most of them are pure iron oxides and ilmenite. By optical microscopy the oxides are identified as magnetite. Most of the magnetite crystals are equidimensional; elongate magnetite crystals are not common. The opaque inclusions in the unzoned core of plagioclase are usually medium size, ranging from 10 to 30 microns. However, grains of magnetite as large as 60 microns together with round pyroxene inclusions are also observed, especially in the large zoned plagioclase crystals. There is no apparent alignment of these inclusions in the unzoned core. However, many opaque inclusions in the oscillatory zone are indeed aligned parallel to the zoning plane. This is especially true for those grains of 2 to 5 microns size. The extremely fine inclusions are randomly distributed inside zoned regions.

The opaque inclusions in biotite are identified as magnetite-rich titanomagnetite and ilmenite. Co-existence of the two phases side by side is not uncommon. Fine exsolution lamellae of ilmenite in magnetite are also observed.

The shape of the opaque inclusions in hornblende is mainly equidimensional. However, there is a significant number of needle or platy shaped grains with axial ratios up to 5:1. These opaques are aligned parallel to the cleavage plane of the hornblende and are identified by X-ray fluorescence analysis as pure iron oxide.

2.2 COOLING HISTORY OF THE TATOOSH INTRUSION

The cooling history of the magnetic phases which record the reversal is important because it is the cooling rate which determines the field averaging by the record, due to the time taken for NRM to be acquired. As will be shown below, the blocking temperature range of the samples of interest is such that about 90 per cent of the NRM is blocked within the temperature interval of 580 and 560°C. We are therefore primarily interested in the cooling rate in this temperature range. We are also interested in the temperature gradient in the intrusion and its motion in this same temperature interval, because they determine the amount of time represented by distance along outcrop section.

Some insight concerning the cooling history of intrusions can be gained by examination of solutions to the linear heat flow equation. However, at the outset it must be noted that lack of knowledge of the geometry of the intrusion makes detailed predictions from such analyses perilous. The error function solutions to the one-dimensional heat flow equation, with appropriate initial and boundary conditions, permit the calculation of the temperature within a cooling igneous mass, in terms of the geometry of the body, its thermal properties and time (e.g. Carslaw & Jaeger 1959). Thus for the infinite half space

$$T(x, t) = T_0 \operatorname{erf}\left(\frac{x}{2\sqrt{\alpha t}}\right)$$

where T is the temperature, x distance and $\alpha = k/\rho c$ the thermal diffusivity, k is the thermal conductivity, c the specific heat and ρ density. The results of analyses of this type have been given in a very convenient graphical form by Lovering (1935) for a variety of intrusion geometries and dimensions. His treatment has been followed in our initial analysis.

The shape of the early southern intrusive phase with which we are primarily concerned is not well known, although it may well be laccolithic. Lovering's analysis for a laccolith illustrates the very long cooling times and low thermal gradients which conductive cooling gives in the body except at the immediate margin. To obtain cooling rates anything like those required to account for our records, the site would have to be within 100 m of the contact of the intrusion. Yet this is in conflict with observed field relations, which suggest that the site would have been between 2 and 3 km from the nearest contact point.

A potentially important effect which has been ignored in Lovering's analysis, but which arises in the cooling of very shallow intrusives such as the Tatoosh, is convective coöling by circulating groundwater. Taylor (1971) has shown that the oxygen isotope ratios for several intrusions in the Cascades reveal contamination by meteoric water. Thus they have δO^{18} values which are not typical of plutons but of meteoric water. It is therefore evident that the cooling of such intrusions is at least partially due to convection in circulating groundwater. Taylor (1971) suggests that the hydrothermal convection system begins operating in the country rocks at the time of initial intrusion. However, within the intrusion itself no circulation gets under way until there is a solidified marginal phase in which cracks can develop and permit the circulation. Once the water is able to circulate in the intrusion it contributes to the heat transfer directly by convection. Taylor (1971) also observed that although the δO^{18} values for the margins of the intrusions reached values -2 which imply considerable exchange, the deep cores of intrusions had values of 5.0, which approach values for uncontaminated intrusives. He suggested that by the time the centre of the stock is solidified sufficiently to permit circulation, the heat source is much reduced and the fractures along which the water migrates have begun to heal with precipitates from the mineralizing hydrothermal fluids.

The effects which Taylor (1971) describes may have a critical effect upon the cooling histories of shallow intrusions. First, the convective cooling of the country rocks means that heat transfer from the intrusion into the country rock is much more efficient than it would be by conductive cooling. Second, the penetration of large amounts of water into the intrusion ensures that the heat transfer within the intrusion itself is much enhanced – the water front may be regarded as defining a region of convective heat transfer surrounding the region in which the less efficient conduction dominates (Lister 1974).

To model the possible effect of convective cooling by the water, we compare conductive cooling with heat transfer in a conducting region with a convective surface. Since the reversal record comes from near to the roof of the intrusion and we are concerned with the earliest stages of cooling, we use the infinite half-space approximation. The initial temperature is taken to be 1000°C. The first analysis is for intrusion into a medium of identical thermal

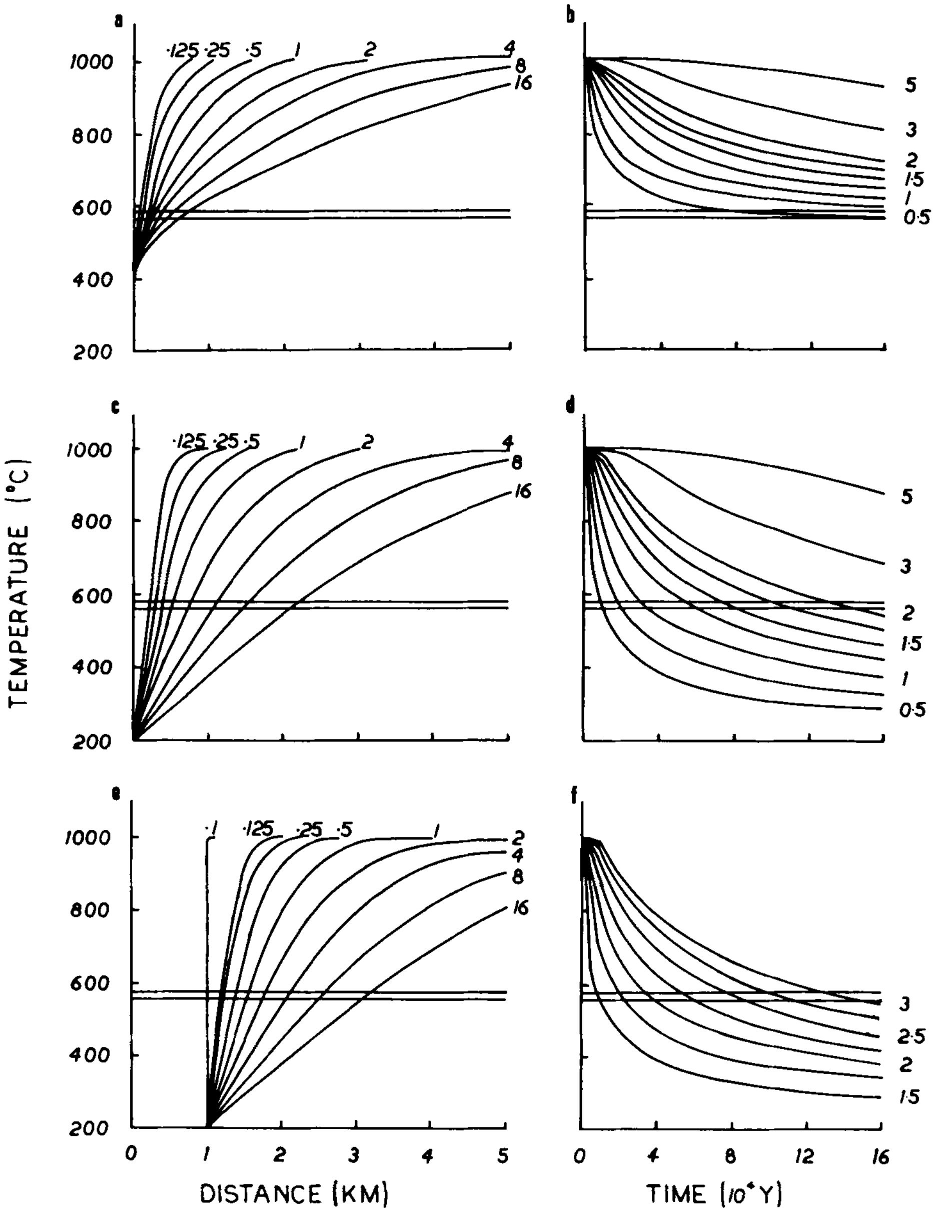

Figure 2. Cooling models for Tatoosh intrusion, (a) temperature–distance and (b) temperature–time plots for conductive cooling model, (c) temperature–distance and (d) temperature–time plots for conductive cooling of intrusion to convective surface at contact, (e) temperature–distance and (f) temperature–time plots for conductive cooling to convective surface within intrusion. On temperature–distance plots parameter is time in 10^4yr. On temperature–time plots parameter is distance in km. Horizontal lines on all plots indicate blocking temperature range.

properties to those of the intrusive rock. This corresponds to the case of conductive heat transfer. Fig. 2(a) shows the evolution of temperature profiles within the intrusion with time. The contact maintains, in this stage of the cooling process, the mean temperature of the initial magma and the country rock. In Fig. 2(b) temperature–time curves for various distances into the intrusion are given. Even at 500 m from the margin, the material takes 80 000 yr to cool through the blocking temperature range which is clearly too long to permit records of secular variation.

Figs 2(c) and (d) illustrate the effect of enhanced heat transfer in the country rock due to the convective heat transfer by the water. This reduces the contact temperature and hence the cooling rate in the margin of the intrusion is increased. At 1 km, cooling through the blocking temperature takes 6000 yr. At 2 km it takes 10 000 yr. These times are still long, but the effect of the water has substantially increased cooling rates. In this simple analysis it is assumed that the circulating water temperature can be used as the temperature at the contact. This neglects the initial contact of the water with the intrusion, which must raise the local temperature of the water much higher.

Following the ideas of Taylor (1971) and of Lister (1974), we assume that cracks propagate into the newly solidified intrusive rock and that the water penetrates the intrusion along these cracks. Again we assume that the circulating water temperature can be used and that this temperature is at the crack front. The concept of a crack front is an oversimplification and the nature of the heat transfer ahead of the front will not be by pure conduction. Water vapour will diffuse into the rock ahead of the cracks and contribute to the cooling. Nevertheless, some indication of the possible effects of water cooling can be seen with this simple model. When the crack front moves into the intrusion the principal effect is that the cooling rate, at a particular point within the intrusion, is controlled in part by its distance from the crack front. The material or Stokes derivative must therefore be used to calculate the time dependence of the temperature, T,

$$\frac{DT}{Dt} = \frac{\partial T}{\partial t} + v\frac{\partial T}{\partial x}.$$

The velocity of the front, v, is not known, although Lister (1974) places it as high as 10 m/yr. However, if this velocity is achieved it can only be so briefly, since the crack front does not penetrate very far into the intrusion (Taylor 1971). Figs 2(e) and (f) illustrate the effect of the motion of the crack front in the intrusion. In this figure the velocity of the front is 1 m/yr and it has been maintained for a thousand years. As Lister (1974) pointed out, a region in the intrusion sees an enhanced cooling rate, first slow and then fast, as the front approaches. The figure illustrates the much enhanced cooling rates near to, but ahead of, the front. If the crack front moves at the suggested 10 m/yr then the temperature profiles in the region of the front are very strongly dependent upon the velocity term in the total derivative. However, at the velocity chosen both terms are important. It is our interpretation that that Tatoosh reversal record site is within about 2 km of the crack front's point of furthest penetration into the body. In such a region the cooling rate in the temperature range of the blocking temperature should be from about 60 yr per degree at 0.5 km from the front to 500 yr per degree at 1.5 km. The corresponding time–distance relations are about 20 and 140 yr per metre.

The convective model defines a two-stage cooling process for the margin of the intrusion which is penetrated by the cracks. Initially the newly solidified rock cools rapidly and the rock temperature soon falls to the circulating water temperature. After this time the temperature does not fall substantially again until the main intrusive mass has reached temperatures comparable to the circulating water temperature of say 200°C. During the initial rapid cooling, as the water first reaches the rock, the high temperature favours rapid exchanging of the oxygen in the felspars (Taylor 1971). The pervasive hydrothermal alteration of the margins of many of the intrusions in the Cascades may well be evidence of the long period of exposure to the circulating water at much lower temperature. Without some such model of mixed convection and conduction it is hard to see how reversals could be recorded with the resolution we appear to see, assuming that the direction change takes a few thousand years.

2.3 ROCK MAGNETISM AND THE ORIGIN OF NRM IN THE TATOOSH INTRUSION

Thermomagnetic curves of bulk samples revealed that the principal magnetic phase in normal, intermediate and reversed samples is a titanium poor titanomagnetite, having a Curie point close to 580°C. Hysteresis plots for samples are shown in Fig. 3 and demonstrate that normal reversed and intermediate samples are not grossly dissimilar. The ratio of J_r/J_s and indeed the overall shape of the loops show that they are dominated by multidomain magnetite. However, the magnetization curve reveals the presence of fine particles (Fig. 4). H_{RC}/H_C is appropriate for a mixture of fine and coarse grain magnetite. AF and thermal demagnetization of saturation IRM and of TRM are also consistent with this interpretation, although they demonstrate that the TRM is dominated by the fine grained carriers, since it has little soft component.

The AF and thermal demagnetization characteristics of the NRM of bulk samples are indicative of predominantly fine grain carriers. Thus the stability of NRM and its relative stability compared to IRM both suggest that little of the TRM is due to truly multidomain carriers. Blocking temperature distributions of samples from normal, reversed and intermediate sections were obtained by thermal demagnetization of NRM and revealed little difference between normal and reversed samples. However, intermediate samples had

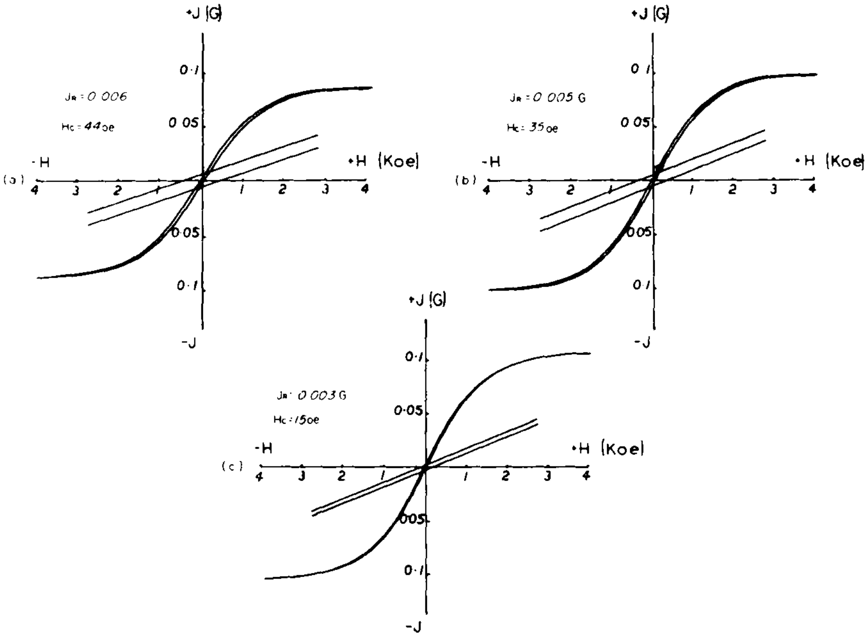

Figure 3. Hysteresis curves for (a) normal, (b) intermediate and (c) reversed samples.

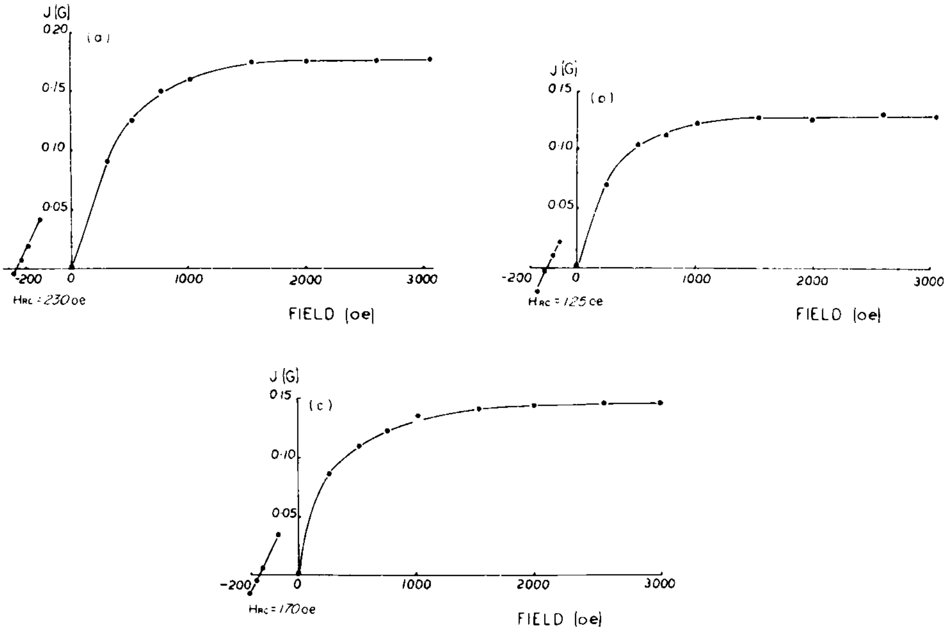

Figure 4. Magnetization curves and remanent coercivity determinations for (a) normal, (b) intermediate and (c) reversed samples.

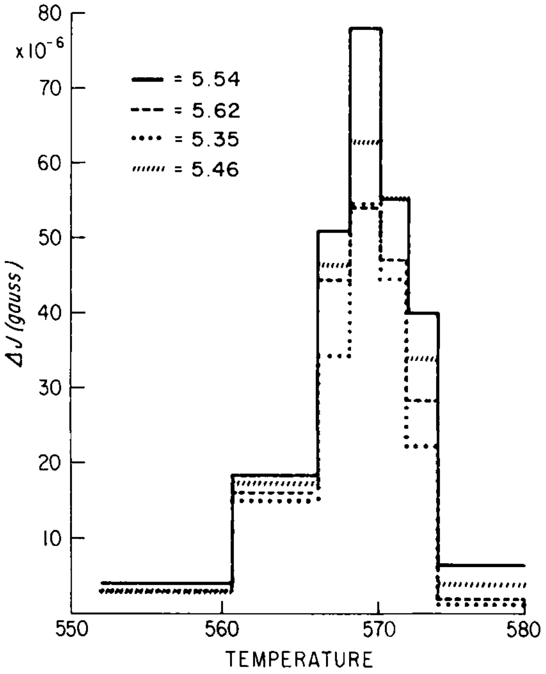

Figure 5. Blocking temperature distributions for samples from reversed part of Nisqually Valley section.

broader distributions which may be due to contamination of the spectra by contributions from the multidomain material. The most detailed study of blocking temperature was made with samples from the reversed region near to Nisqually bridge. Results from four samples are shown in Fig. 5 and reveal that the blocking temperature is indeed narrow with more than 90 per cent of the TRM being acquired within the temperature interval between 560 and 580°C.

Microanalysis of the NRM and its carriers (Wu *et al.* 1974) led to the recognition of two different types of NRM carriers. In the plagioclase felspar remanence is carried by fine grain magnetite, characterized by high Q_n' or Q_t values, low initial susceptibility, and high stability against AF and thermal demagnetization. Hysteresis parameters have been difficult to obtain because of the extremely small mass of total magnetite in these feldspar crystals. However, values of J_r/J_s of 0.1 have been observed. This type of carrier and its associated NRM which is also stable and shows single domain-like AF demagnetization characteristics has been termed Type A (Fig. 6). It appears to be similar to that described by Hargraves & Young (1969) in other intrusive rocks. Our results confirm their ingenious experiments with the felspars in the Lambertville diabase. In contrast, a Type B NRM has been defined which is due to coarse magnetite found primarily in association with biotite but to a lesser extent in hornblende. This magnetite carries soft unstable remanence, has low Q_n' values, high initial susceptibility, low coercive force and low saturation remanence to saturation magnetization ratios, indicating that it is indeed multidomain. On AF demagnetization of this NRM the material tends to give a minimum noise contribution at a value of about 100 Oe, but on the application of higher fields there is a tendency to acquire remanence which is contamination (Fig. 6).

Although it now seems clear that the stable NRM which we use in the reversal study is carried by fine grain magnetite, predominantly in the felspar, it is not completely clear what the origin of this magnetite is. It could have been included in the felspar at the time of crystallization of that mineral, or it could have subsequently exsolved from the felspar lattice. The association of cloudy felspar with the exchanged δO^{18} values suggests that the

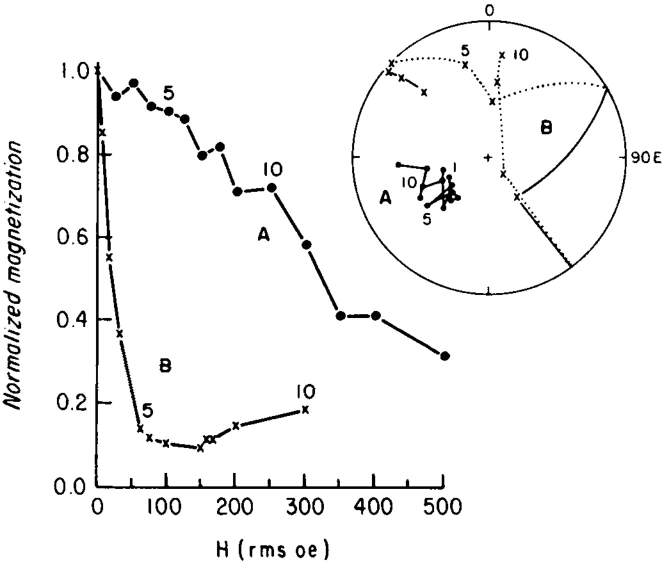

Figure 6. AF demagnetization for types A and B NRM.

formation of at least some of the magnetite is linked to the hydrothermal events.* The origin of the magnetite in the felspar has been discussed earlier (Wu *et al.* 1974). At that time we noted that at least some of the magnetite was probably included in the felspar crystal at the time of initial growth of that mineral. However, we were unable to demonstrate how much of the magnetite was indeed formed at high temperature and most importantly whether formation was above or below the Curie point. Recently we have returned to this problem. Thermomagnetic analyses under vacuum revealed that upon heating to 600°C no significant change in J_s was produced in felspar separates. Thus, the magnetite in the felspar was not generated by a reversible process below 600°C. In contrast the J_s value for the whole rock increases upon heating to the same temperature under the same conditions. Thus the magnetite in the felspar is in equilibrium with the rock to 600°C, but that in the ferromagnesian minerals is evidently of low temperature origin since reheating gives more magnetite. This is consistent with our earlier interpretation that the magnetite associated with ferromagnesian minerals is of low temperature origin and probably related to the hydrothermal alteration at relatively low temperature but that the felspar magnetite is of higher temperature origin. From comparisons of the stability of NRM in a number of intrusions in the Cascades with the δO^{18} values, it appears that at least some of this felspar magnetite is formed during the initial high temperature exchange of the felspars. It therefore appears that the NRM record is carried by felspar magnetite having a high temperature origin. It should therefore carry primary thermal NRM. Nevertheless we cannot entirely rule out the possibility of some thermo-chemical NRM carried by magnetite formed below its Curie point.

2.4 THE GEOLOGICAL AND PHYSICAL BASIS FOR INTERPRETATION OF THE PALAEOMAGNETIC RECORD OF THE TATOOSH INTRUSION

When we combine the geological and rock magnetism studies described above, we see that the stable NRM of the Tatoosh is most probably of thermal origin carried by fine magnetite. When we compare the blocking temperature spectra of the samples with the proposed cooling histories, we see that if conductive cooling models are invoked, the time-averaging involved in the acquisition of NRM precludes the observation of secular variation behaviour with time constants less than some 10^3yr. However, if the convective cooling model is invoked and the magnetite is indeed carrying thermal primary NRM, then considerably higher resolution is to be expected.

3 Palaeomagnetism of the Tatoosh intrusion

3.1 INTRODUCTION AND PRINCIPAL FEATURES OF THE REVERSAL RECORD

After the initial collections had led to the choice of Nisqually Valley as the best area in which to try to obtain a detailed reversal record, a number of reconnaissance sections were collected in order to establish where in the valley the reversal actually occurs. The results from two sections, one from each side of the valley, were published in our preliminary description of the data (Dunn *et al.* 1971). Subsequently several other sections have been collected in attempts to establish the behaviour of the field during the reversal in more detail. These sections are shown in the map of Nisqually Valley (Fig. 7). Some of the East Side outcrop is also shown in the photograph (Fig. 8).

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* If fine grain magnetite is formed hydrothermally in the upper and marginal parts of intrusions, it may also be formed in equivalent parts of oceanic layer 3 intrusives and play a role in sea floor magnetic anomaly stripes.

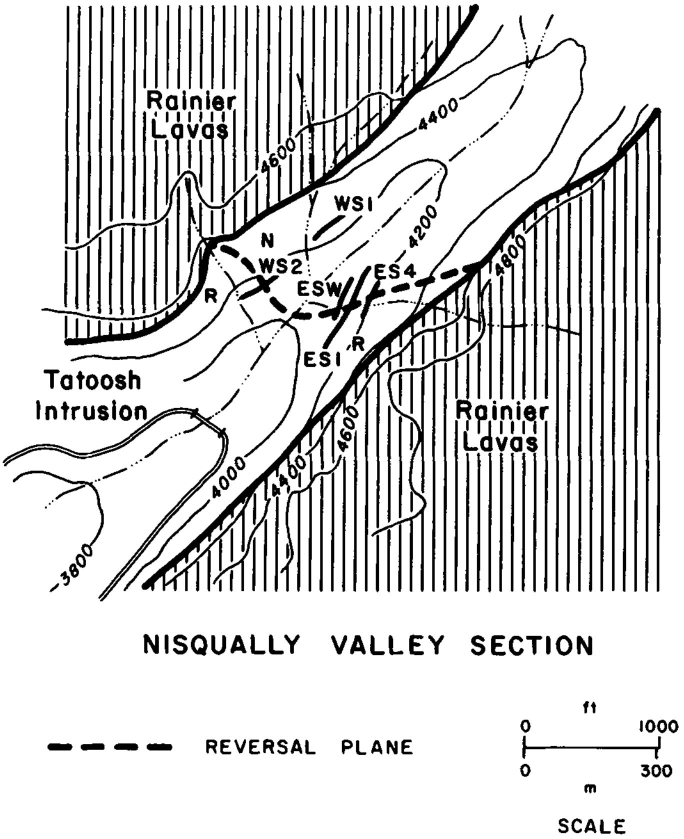

Figure 7. Map of Nisqually Valley showing reversal plane and sections.

Three of the sections shown in the map, i.e. First East Side (ES1), First West Side (WS1), and Second West Side (WS2), were of a reconnaissance nature with spacings of as much as a metre between some samples. They will not be discussed further although the results are included in the summary plots. The remainder of the sections were collected in the vicinity of the reversal and with much higher sampling density. These sections are the Winter section (ESW), the third and fourth level sections (ES3, ES4), and the cliff section (ESC). Vertical cores were drilled near to the Nisqually bridge (NBC) and at the three core sites close to the reversal region (TRC). The reason for this profusion of sections is simply that it soon became apparent that the records were noisy and that the only hope of establishing the behaviour during the reversal in any detail would be to demonstrate that similar results were obtained from more than one section across the reversal.

Samples were subjected to AF demagnetization to 100 Oe. This value may not eliminate all of the soft noise carried by the samples, but since the microanalysis study revealed that demagnetization to higher fields resulted in acquisition of spurious magnetization by large soft multidomain grains of magnetite, the 100 Oe value was accepted as a compromise.

Results were initially presented in the form of plots of declination, inclination and intensity against distance along outcrop (e.g. Dunn *et al.* 1971) in which the first East and West side reconnaissance sections were given. To gain an impression of the broad features of the reversal all the results were later presented on a single plot in the following way. The

Figure 8. Photograph of east side outcrop.

samples were located on a three-dimensional grid and the inclination data fitted to a function analogous to the Fermi distribution function to define the reversal plane. The function has the form

$$n_{\mathrm{Fermi}}(E)=\frac{1}{\exp\,[(E-E_0)/kT]+1}$$

(e.g. Eisberg & Resnick 1974). The plane so defined had a strike of 290° and a dip of 30° S. It is interpreted as the blocking temperature isotherm at the time of the reversal onset, and served as a base plane for distances in the Nisqually Valley. In Fig. 9 Fisher (1953) means are plotted as a function of distance normal to this plane. Along section, Fisher's analyses were carried out on samples within successive 1.5 m intervals in the densely sampled regions and every 3 m elsewhere. The record reveals that (1) the intensity of NRM decreases substantially before the onset of directional changes, (2) the declination change is gradual at first but the inclination changes rapidly initially, (3) the dispersion of directions, as measured by the Fisher precision parameter *K*, increases markedly during the reversal, reaching a maximum at the time of minimum intensity of magnetization.

As an alternative presentation of the data, the results are plotted as a succession of VGP's (Fig. 10). It should be noted that this is not intended to imply that the field was

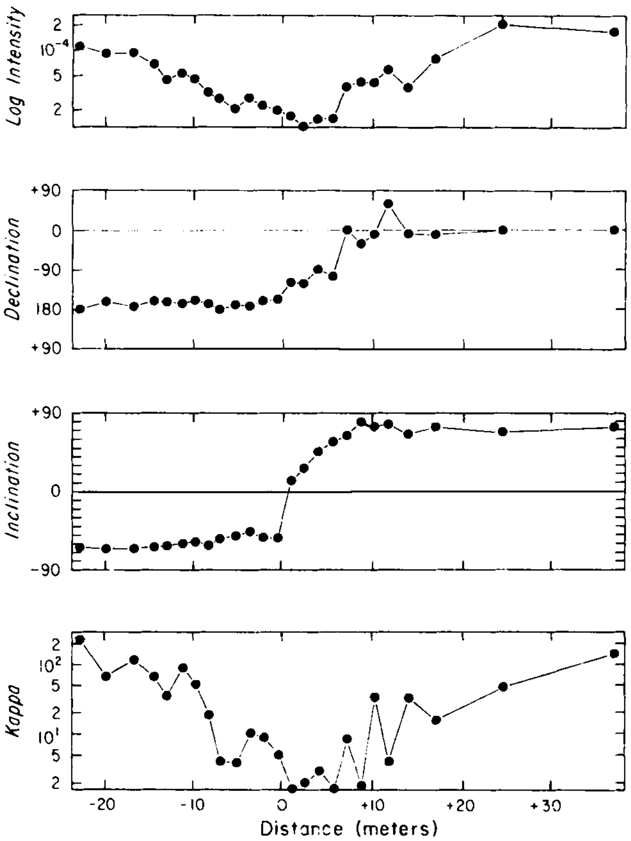

Figure 9. Declination, inclination and intensity of Fisher means plotted against perpendicular distance from reversal isotherm plane.

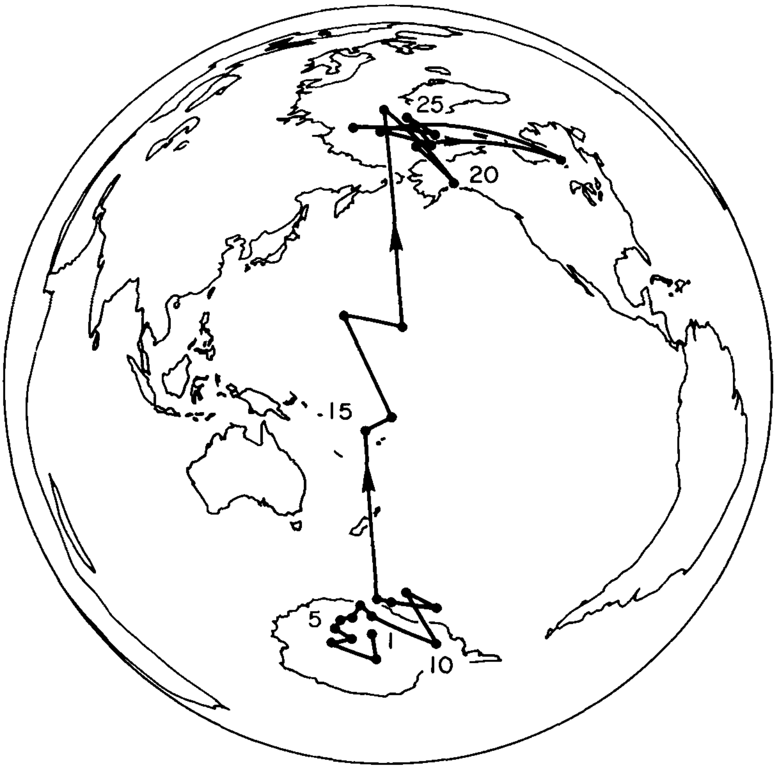

Figure 10. VGP path for reversal using Fisher mean values.

dipolar during the reversal. It is simply that VGP's afford a convenient presentation, particularly if comparisons between different records are to be attempted. The resulting plot reveals that the reversal path is somewhat confined in longitude, crossing the equator near to the centre of the Pacific Ocean.

As we noted previously (Dunn *et al.* 1971), there are basically three reasons, which considered in conjunction, convince us that the Nisqually sections record a true field reversal, and that neither complicated mineralogical changes nor reheating with the superposition of a later magnetization of opposite polarity can explain the observations. First, the distribution of normal, reverse and intermediate rocks within the intrusion is not random, but gives a relatively simple pattern which can be explained by the movement of the cooling front through the body, in a manner similar to that proposed by Wright (1960). Second, the low intensity of magnetization of the intermediate samples is due to the acquisition of remanence in a weak field throughout the high range of blocking temperatures. It is not due to the acquisition of remanence in a normal field in one temperature range with a reverse magnetization in the remainder. Such a magnetization gives a different thermal demagnetization curve quite distinct from that observed in these samples. Third, the stable magnetization of these samples is carried by fine grain magnetite for which no self reversal mechanism has been observed or predicted.

If the results are examined in this manner, they give an overall impression of the reversal, which we interpret to be of $R \rightarrow N$ type. However, to gain more insight into the reversal process, we consider in detail the higher density sequential sampling.

3.2 VERTICAL CORES

Vertical cores were taken at two sites. The first was immediately upstream of the Nisqually bridge on the west side of the valley. The second site was nearer to the reversal region, where three cores were obtained very close to each other to see how well the records correlated. Neither core site was in a region in which the NRM was fluctuating very strongly and so they afford records of the field some time before the onset of the reversal in direction.

3.2.1 Nisqually bridge core

A 10 m, 4.3-cm diameter core was recovered from the Nisqually bridge drill hole. Near the top, it was broken into lengths of less than a metre. However, towards the bottom of the core it was possible to maintain orientation over lengths of as much as 2 m. Declination, inclination and intensity of NRM as a function of distance down hole are given in Fig. 11. Declination was obtained for the lengths towards the bottom of the core by setting the average value of a given length to be 180°. Although it would be possible to orient the cores roughly by using their soft component, this method is not adequate for secular variation analysis.

The records are clearly noisy at this resolution, with one-point anomalies apparent such as in the inclination plot at a depth of about 4–5 m. Yet, there also appeared to be some features of interest, so the declination and inclination data were smoothed with low-pass filtering. The curves superposed in the figures were the results of filtering with rejection at 2.6 m. When these data are plotted in the form of declination versus inclination diagrams, the raw data exhibit rapid and erratic fluctuations, which can be seen to be progessively smoothed with increasingly heavy low-pass filtering to give essentially anticlockwise loops (Fig. 12). In an attempt to assess the significance of such a procedure, we smoothed random

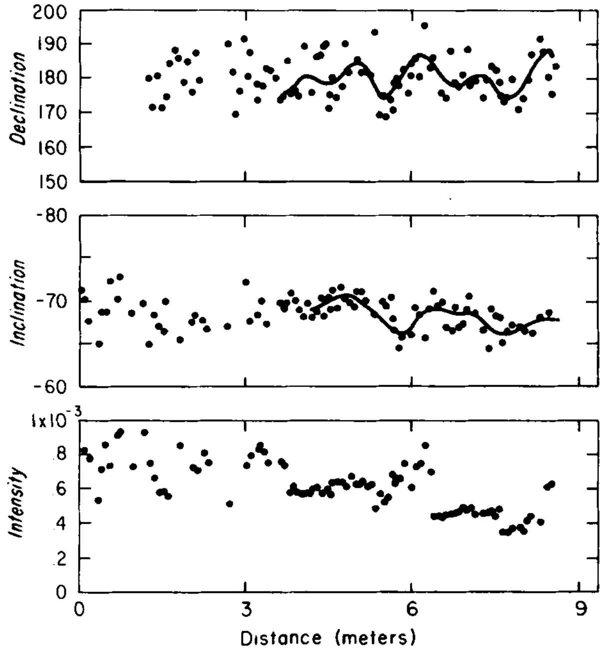

Figure 11. Raw data from Nisqually bridge core.

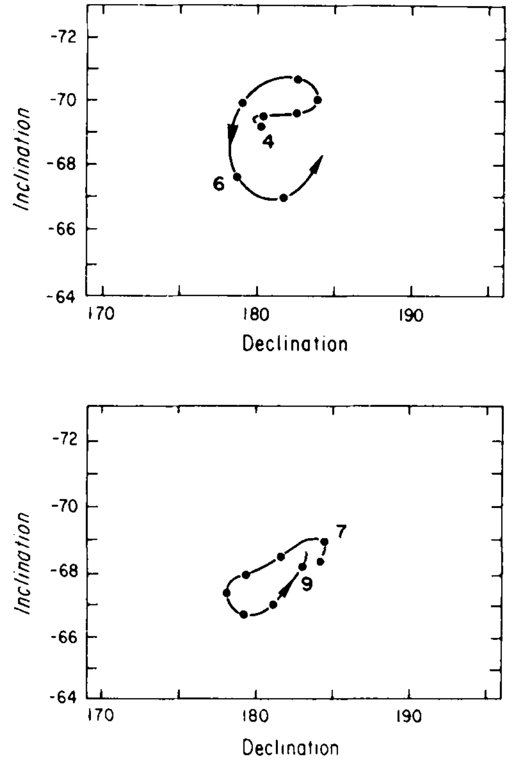

Figure 12. Bauer diagrams for smoothed data from Nisqually bridge core.

sequences of the data. In contrast to the true sequence, these random sequences gave much smaller mean dispersion with the same filter and did not show the systematic anticlockwise loops. When declination and inclination means were calculated for discrete intervals down core, similar anticlockwise loops were generated. Finally, when running averages of declination and inclination were calculated, the same type of behaviour was once again observed. We therefore conclude that the patterns in Fig. 12 are not due to noise but represent a degree of serial relationship between the observed directions of magnetization giving predominantly anticlockwise loops in this core.

The declination versus inclination plots are presented as if one is looking along the line of force of the geomagnetic field in the direction that a north end of a compass would point. The motion of the field vector with the passing of time can then be thought of as defining a small cone such that anticlockwise loops are predominantly defined during this time of reversed field. This is analogous to the Bauer (1899) diagrams of recent secular variation in a normal field time, but the sense of motion of the vector is in that case clockwise. The VGP path viewed from above the Earth's surface in the appropriate hemisphere has the same sense of rotation as the Bauer diagram.

Presented in the form of these Bauer diagrams, the palaeomagnetic record from the Nisqually bridge defines predominantly anticlockwise loops, with varying wavelengths from about 3 m to little more than 0.3 m. There is also a decrease in intensity with depth in the core and it appears as if a large anticlockwise loop is associated with each of two features in the intensity record in the bottom half of the core.

3.2.2 Three core experiment

At another site, three cores were drilled at the corners of an equilateral triangle of side 0.2 m to see if any correlation could be seen between the different cores and, if so, whether it would be possible to define the orientation of the cooling front by the correlation of features in the different cores.

Measurements of individual samples revealed that there was somewhat more variation in declination and inclination over comparable core lengths than was found in the Nisqually bridge core. Some possibly significant correlations are apparent. Features define loops in declination versus inclination plots or Bauer diagrams. However, in length down core, these loops are equivalent to the shortest wavelength features defined in the Nisqually bridge core. We have been unable to correlate these features uniquely within the short lengths of core available. Nevertheless, the three cores do show a common decrease in intensity around a depth of about 0.5 m. We conclude that although there may be some correlatable features in these cores, one cannot isolate features which have wavelengths shorter than approximately 1 m in these vertical cores.

3.3 DENSELY SAMPLED SECTIONS FROM THE REVERSAL REGION

These sections come from the East side outcrop (Fig. 7) and afford closely spaced data from the reversal region. The fourth (ES4) and Winter sections (ESW) are roughly horizontal, but the cliff section is collected approximately perpendicular to the interpreted cooling front at the time of the reversal. The results are given in the form of plots of declination, inclination and intensity as a function of distance from the cooling front in Fig. 13. The volume intensity of NRM after 100 Oe AF demagnetization is plotted in units of Gauss and used as a direct indication of field intensity. As we pointed out earlier (Dunn *et al.* 1971) Thellier–Thellier determinations were broadly consistent with the results from the direct use of the NRM after demagnetization.

The fourth section provides data furthest from the reversal plane and gives the best evidence of the decrease in intensity prior to the reversal in direction. Throughout much of the length of the section the decrease in intensity can be followed, while the change in direction does not set in until about halfway along the section. Plotting the intensity on a logarithmic scale indicates that the decrease follows a power law for one order of magnitude from −18 to −6 m. There is some indication of short wavelength variations, but the predominant effect is of a steady decrease by about an order of magnitude. With the possible exception of a minor fluctuation in declination and inclination at about −7 m, there is no significant change in direction until the onset of the reversal. By +3 m both inclination and declination are approaching a normal value.

The overall pattern of the Winter-section results is similar to that found in the fourth level section. The NRM intensity is much reduced compared to the values observed further away from the reversal plane. In the intensity record there are indications of structure within the decrease, but the fluctuations in intensity make the definition of fine structure unreliable.

The cliff section, unlike the fourth level and the Winter sections, continues beyond the intensity minimum so that one sees the beginning of the recovery of the intensity of the normal field. These results were obtained by initial AF demagnetization to 50 Oe followed by thermal demagnetization to 300°C, by the stepwise method. The pattern of directional and intensity changes is again broadly similar to that seen in the other two sections. Note however that if our correlations are correct then the normal inclination at +3 m in the other records is followed by negative values before recovery of the normal field.

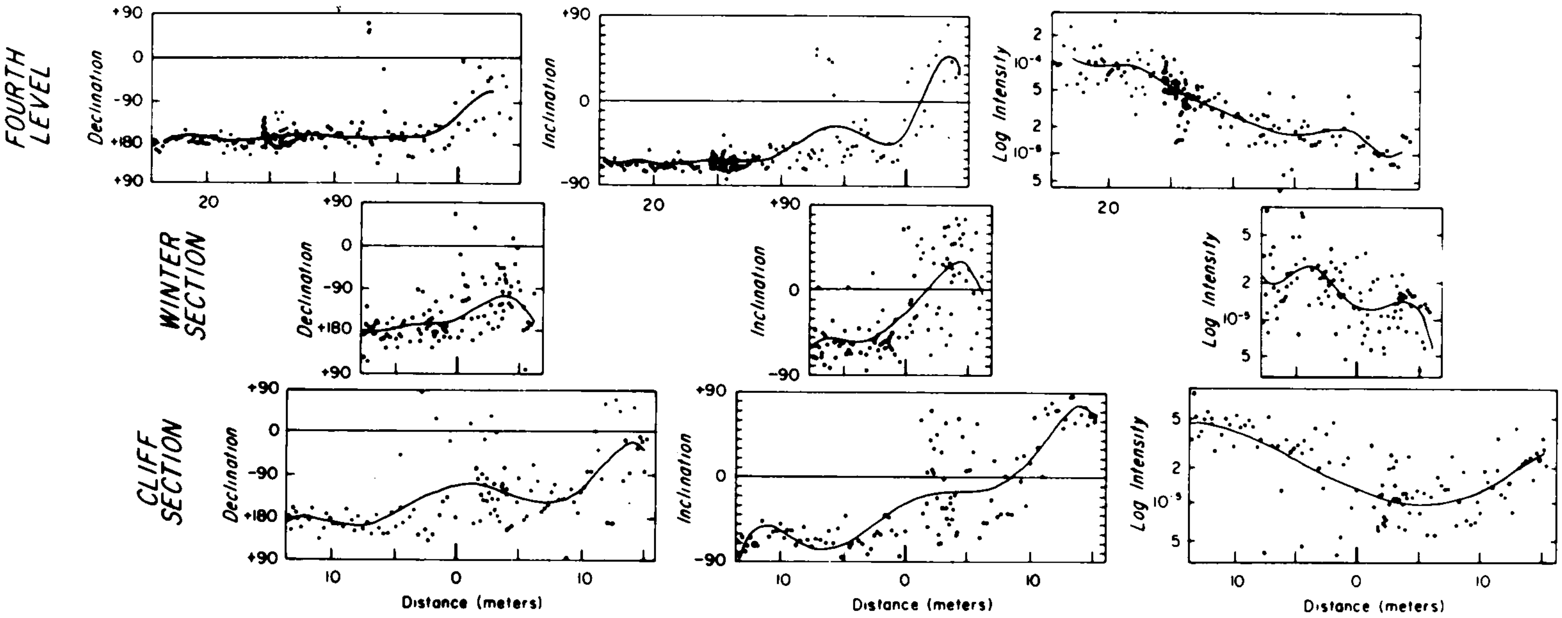

Figure 13. Raw data for reversal sections in Nisqually Valley.

Figure 14. VGP path of part of cliff section record.

The results for the high density sections can also be presented in the form of VGP paths. Such paths include intriguing features similar to the loops seen in the Nisqually bridge core, although they are much enhanced in size. The results for part of the cliff section are shown in Fig. 14 as raw VGP positions. Immediately prior to the part of the section illustrated the VGP positions are centred on Antarctica, with erratic swings between successive pole positions common. The centre then shifts to near to New Zealand as shown in the figure. The erratic changes continue about this centre. Eventually a single partial clockwise loop brings about a transition to high altitude poles appropriate for the normal field configuration. Thus there appears to be some fine structure in the reversal in the form of an intermediate centre of VGP positions, with rather rapid changes from the reversed field to the intermediate centre and from it to the normal configuration.

If the paths are heavily smoothed all three high density sections give results similar to the mean path already shown in Fig. 10. They are confined in longitude to the same part of the Pacific. Evidently after heavy smoothing all records whether obtained by AF or thermal demagnetization give an essentially common path.

3.4 SUMMARY OF THE PALAEOMAGNETIC RECORD OF THE TATOOSH

The palaeomagnetism of the Tatoosh section in Nisqually Valley appears to record a $R \rightarrow N$ field transition at about 17 Myr. The intensity of remanence of the intermediate samples from the transition is more than an order smaller than that of the normal and reversely magnetized samples. This variation is seen in all sections which extend into the reversal region. The record clearly indicates that the intensity change sets in before the directional change. On the log normal plots on which the results of intensity were presented for the densely sampled sections the decay appears to be roughly linear. The decay rate is such that a distance of about 20 m gives a reduction in the intensity of NRM by one order of magnitude. The intensity then remains close to its minimum value for about 10 m, before the recovery begins. There was not any evidence of a major increase in intensity during the intensity minimum. The directions of remanence of individual samples exhibit small scatter until the intensity approaches its minimum value. The scatter then increases. The reversal in direction is completed in the part of the sections in which the intensity is close to the minimum value. There is a much sharper change in inclination than declination. The reversal in direction, as traced by the mean values along section, is achieved by a VGP path which is somewhat confined in longitude and lies within the western Pacific. The raw data reveal evidence of loops and swings in the VGP paths. During the actual reversal they are on a scale of tens of degrees (Fig. 14). The early state of the reversal involved erratic swings about Antarctica and then New Zealand. During the remainder of the reversal the path is less erratic – the intermediate to normal configuration is achieved by a single large clockwise loop. The recovery of the normal intensity is not seen in detail, so we cannot be sure whether the time constants of the recovery are the same as those of the initial decay. Nevertheless the process does not seem to be grossly asymmetric.

4 Interpretation of palaeomagnetic record in terms of geomagnetic field changes

A palaeomagnetic record afforded by a sequence of rock samples is related to the field changes at the time the magnetization was acquired in a complicated manner. For example, there are observer errors in both orientation of the samples in the field and in measurement of the remanence. There are noise contributions from failure to isolate adequately the primary NRM from viscous or soft contamination. Problems may also arise from the sampling interval used in the collection. Finally, in addition to these effects which are essentially distortion introduced in the playback system, distortion is introduced as well in the recording process. As long as we are only concerned with the field changes corresponding to the principal changes in the palaeomagnetic record, the effects enumerated above are probably not crucial. However, if we are interested in detailed secular variation records, then it is the failure to be able to determine the system response adequately, which ultimately frustrates our efforts. We now consider the interpretation of the field changes from the palaeomagnetic record described in the previous section, beginning with an attempt to define the important contributors to the distortion.

4.1 OBSERVER ERRORS AND DISTORTION OF THE GEOMAGNETIC FIELD CHANGES RECORDED BY THE PLAYBACK PROCESS

Orientation errors are at least at the one degree level, except in the continuous core measurements, where the relative accuracy is clearly considerably better. Repeat measurements of magnetization of the samples demonstrated that, with the exception of some of the samples from the centre of the intermediate region, precision is to better than one degree in direction and to 1 per cent in intensity. Repeat AF demagnetization at a single field strength, in all but some of the intermediate samples, again gave insignificant errors of less than a degree in direction and 1 per cent intensity. Confirmation of these error assessments came from analyses of the remanence of the long core. It was possible to observe successive directional changes between samples of little more than a degree and even to cut samples in half and observe successive sub-sample differences at a fractional degree level at some places in the core. However, elsewhere in the core, one-point anomalies of much greater magnitude are seen and it seems reasonable to assume that other sources of noise are of more importance than the errors associated directly with the measurement. We conclude that with the possible exception of some samples from the intermediate region measurement errors are not the limiting factor in this study.

Samples from the intermediate region pose problems not generally encountered in palaeomagnetism. Part of the difficulty is evidently related to the low intensity of magnetization during the reversal in direction. This gives rise to a smaller primary NRM signal. Yet, there is no reason to suppose that the noise generators recording the present field at the site and the various laboratory fields to which the samples are inadvertently exposed are any less efficient than in other samples. Hence, there is a signal-to-noise reduction of at least an order of magnitude. As an example of the types of problems encountered, we note that certain intermediate samples from the cliff section gave quite erroneous results, when they were exposed to the Earth's field between the time they had been thermally demagnetized and their measurement. When they were subsequently thermally demagnetized and kept in field-free space prior to measurement, the problem disappeared. Neither the normal nor the reversed samples showed such effects. In fact the Tatoosh is an excellent recorder for the stable geomagnetic field strength.

The sampling interval can strongly affect the appearance of the declination, inclination and intensity plots and indeed of the VGP paths. The appearance of plots of declination and other parameters against distance along section are particularly affected by the sampling interval, if the individual sample results are joined by lines. This is partly due to the enhancement of departures from a local mean value. Since at least some of these are certainly noise, it is not wise to assign much meaning to individual spikes in the records. The recovery of reversed inclination by individual points should not be regarded as defining a characteristic pattern for the reversal even if they are not due to noise, unless the section is continuous or very densely sampled.

To reduce the effect of noise, a variety of smoothing techniques have been tried. The continuous cores have constant sampling intervals and have been analysed with running averages of the components, running Fisher averages and low-pass filtering. In the various sections of individual drill samples, Fisher averages for particular lengths along section have been used. It appears that at the level of smoothing required there is little to choose between the various methods on a practical basis. Thus all methods give indications of severe noise contamination if resolutions of less than a metre or so are attempted. With longer wavelength features all methods seem to smooth to give comparable results.

4.2 FIDELITY OF THE RECORDING PROCESS

Having considered the errors in observation and the effect of the sampling interval, we now consider how faithful a record of the geomagnetic field the intrusion is likely to generate. This turns on the distortion due to the recorder itself rather than on the playback or measuring process. As we noted earlier, the two parameters which are required in order to interpret the palaeomagnetic record in terms of changes in the geomagnetic field as a function of time (assuming that the NRM is indeed thermal in origin) are (1) the time taken to cool through the blocking temperature distribution, and (2) the motion of this temperature range through the body.

The time taken to cool through the blocking temperature distribution determines the number of years over which the NRM averages. However, the actual distribution of the blocking temperature within the range determines the weighting function or system function of this averaging process. It is fortunate that the blocking temperature distribution is so narrow in these samples (Fig. 5). To acquire 90 per cent of the NRM assuming pure conduction models will involve times of several thousand years at any resonable estimate of distance of the Nisqually section from the margin. If convective transfer is invoked this could give averaging times for the acquisition of NRM of several hundred years to a maximum of 2000 yr. Such times would mean that if the secular variation of the geomagnetic field was similar 17 Myr ago to what it is now, the features would be heavily smoothed but one should still be able to see them.

4.3 GEOMAGNETIC FIELD CHANGES IMPLIED BY THE PALAEOMAGNETIC RECORD FROM THE TATOOSH

The first aspect of the record to be considered is the relationship between the observed variation in intensity of stable remanence after AF demagnetization and the intensity of the ancient field. In this work we have not relied heavily upon the Thellier–Thellier (1949) method of intensity determination, although a number of determinations demonstrated that the observed relative variation in remanence correlated well with the absolute variation obtained from the Thellier–Thellier determinations (Dunn *et al.* 1971). Part of the reason for not undertaking a major program of Thellier–Thellier determination was that we obtained increasingly puzzling results as we tried to refine the earlier estimates by application of the Thellier–Thellier method. For example, we observed that the remanence acquired in the laboratory intensity determination appeared to be a non-linear function of the intensity of the NRM carried by the sample initially. We have therefore been content to obtain some indication of the relative changes from the intensity of remanence itself rather than attempting to follow the details of the absolute changes by normalization procedures. We have however used $\mathrm{IRM_s}$ normalization to ensure that we do not mistake the effect of gross changes in lithology for field intensity fluctuations.

The time taken for the reduction in intensity is clearly an important aspect of the reversal process. Unfortunately, without making further assumptions, we cannot obtain an absolute time estimate from our record. However, the ratio of the time taken for the reversal in direction to the time of the fluctuation in intensity is available. Moreover, since there are systematic changes in direction of magnetization, within times shorter than the intensity decay, it is clear that the change in intensity is not simply a smoothing effect. Rather, the intensity changes reflect different field strengths just as the directional record demonstrates changes in direction on a time scale shorter than the decay itself.

To place absolute time estimates on the reversal process involves making assumptions which can only be poorly justified at present. Nevertheless, the cooling models do place some constraints on the reversal time. If we assume that the time taken to cool through the blocking temperature distribution is no more than a thousand years, then the site must be within 0.75 km of the furthest penetration of the crack front into the body. This then gives an estimate of 60 yr/m for the time–distance ratio perpendicular to the isotherms. From Fig. 13 an estimate of at least 20 m for the change in direction is evident and a distance of more than 50 m for the change in intensity is obtained if the latter is assumed to be symmetrical about the minimum. These distances give times of 1200 and 3000 yr for the directional and for the intensity changes. While these times are short compared with currently accepted times for reversals, they are probably as good as can be expected with so simple a working model. The major difficulty which has been encountered is that if the cooling rate is made sufficiently fast to account for the acquisition of NRM with sufficiently good resolution, then the motion of the isotherms is so fast that the time along section becomes unrealistically short. The water cooling model improves the cooling rate without enhancing the penetration rate of the isotherms critically, but it is clear that the cooling models are only moderately successful in explaining the observed records. Hence, we feel that it would be unwise to use our work as an indicator of the absolute time involved in reversals until we have more successful cooling models.

In view of the difficulty encountered with the cooling models, it may be advisable to use other estimates of the absolute time taken for the reversal in direction (e.g. Harrison & Somayajulu 1966) and to use only the ratio of the time of directional and intensity changes from our work. This method then gives about 10 000 yr for the intensity change. This in turn gives time–distance relationships along section of about 200 yr/m.

The changes in local field directions implied by the records are an important aspect of the study. If the records are heavily smoothed then we obtain time-averaged paths which reveal that the reversal is achieved by a steady change in declination dominated by westerly declinations. In contrast the inclination changes rapidly at the time of intensity minimum and then more gradually.

If the records are averaged less heavily, or if the raw data are used, looping and swinging in the VGP path on a time scale of one-fifth to one-tenth of the reversal time are seen. Assuming a time–distance relationship along section of between 100 and 200 yr/m these features have periods of a few hundred years. Anticlockwise rotation when the VGP is in the northern hemisphere is consistent with the predominant effect at the present time of clockwise rotation. The usual interpretation is that local non-dipole sources carried westward past the site cause such features (e.g. Runcorn 1959; Skiles 1970). It should, however, be noted that the sense of rotation does not uniquely give the sense of drift (e.g. Dodson 1977). There may be features with still shorter periods of one-fiftieth the time taken for the reversal in direction, but at present it is not possible to separate them reliably from the noise.

5 Laurel Hill intrusion reversal record

A second reversal record was obtained from the Laurel Hill intrusion near Mount Hood in western Oregon (latitude 45° 20′ N, longitude 121° 40′ W) and a preliminary description published some years ago (Ito & Fuller 1967). The intrusion, like the Tatoosh, is shallow and the record from the uppermost part of the exposed mass. Its age is 8.2 ± 0.55 Myr.* The Laurel Hill intrusion is thus considerably younger than the Tatoosh. The record was obtained primarily from a road section, which climbs up from the region of the contact towards the centre of the exposed mass. This is evidently very close to the original roof of the intrusion. The section does not cut sharply across the cooling isotherms, but may be almost parallel to them. The reversal record was obtained over a section of an order of magnitude larger than that of the Tatoosh reversal record. The rock is a granodiorite and has rather more of the coarse grain unstable magnetite than does the Tatoosh in the Nisqually Valley. There is strong evidence (Taylor 1971) that the exposed outcrop of the Laurel Hill body was contaminated and cooled by meteoric water. As we noted above, the same effect may be important in the Tatoosh, but since the Nisqually Valley section is further into the intrusion and was probably not reached by the water the effects are much less in the Tatoosh than in the Laurel Hill intrusion.

The raw data for the Laurel Hill reversal are shown in the form of declination, inclination and intensity against distance in Fig. 15(a). It is evident that there is little change in intensity associated with the directional change. The data are also shown as VGP plots for the major part of the change in direction (Fig. 15(b)). The plot starts at a distance of −50 m in the

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*We are grateful to M. Bikerman (University of Pittsburgh) for the separation work for the age determination, and to B. Dalrymple (USGS, Menlo Park) for the K/Ar age determination.

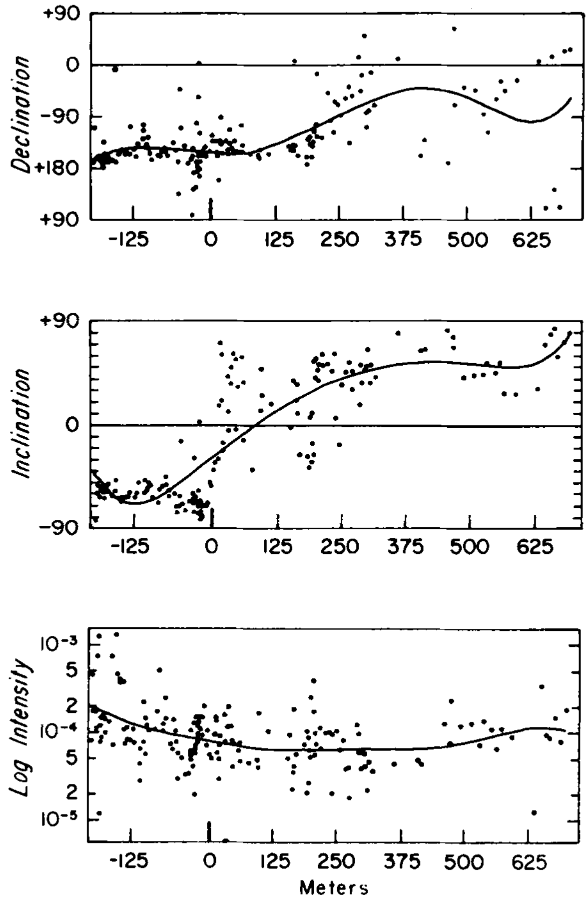

Figure 15 (a)

Figure 15. Laurel Hill reversal record, (a) raw data declination, inclination and intensity, (b) part of VGP path using raw data.

section. Initially there are major swings, which are essentially declination swings about a mean pole position somewhere in Antarctica. There is then a major change in pole position to a region east of New Zealand. Looping and swinging about this position then ensue. Finally the normal configuration is acquired by further erratic swings and loops.

The absence of an obvious intensity change may be due to the limited extent of the section. If the relation between intensity and directional changes in this intrusion is the same as in the Tatoosh the major intensity decrease will have been completed before the record starts. The VGP path reveals a variety of intriguing loops and swings, which are unfortunately almost certainly contaminated by noise, so that it is not wise to interpret individual loops in terms of secular variation anomalies. However, the pole seems to be centred about two separate regions within the first part of the reversal with little indication of a transition between the two.

The raw data for the Tatoosh and Laurel Hill reversals can be compared in Figs 13, 14 and 15. Both records appear to have somewhat similar trends. In Fig. 16 the time-averaged paths

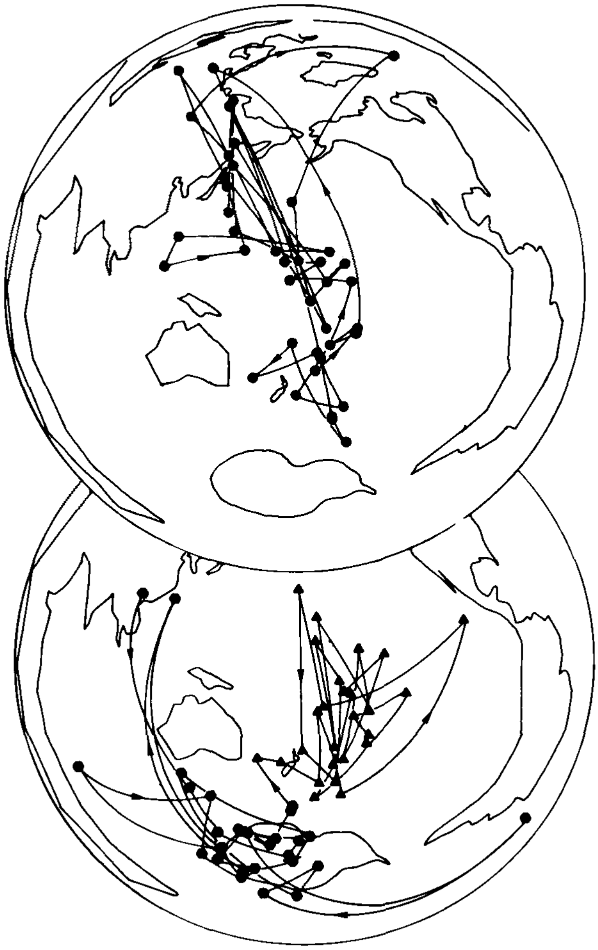

Figure 15 (b)

are compared. The single Laurel Hill section has been averaged at 100 m intervals to obtain a record with comparable sampling density across the reversal to that of the Tatoosh record. Even allowing for the possibility that the section is far from perpendicular to the isotherms, it appears that the blocking temperature isotherms moved much faster here in the Laurel Hill section than in the Tatoosh section. If the length of reversal transitions does turn out to be similar, then the difference in the section length in these two bodies may be rather dramatic evidence of the effect of water cooling of the type suggested by Taylor (1971) and Lister (1974). The Laurel Hill section probably comes from the region penetrated by the water, while the Tatoosh site lay ahead of the crack front. The Laurel Hill record is shown in Fig. 16 as superposed on the Tatoosh record. The VGP paths are given in Fig. 16(b). Not only are the two paths confined in longitude, but the paths traverse the same part of the Pacific Ocean. Moreover, the detailed relationship between declination and inclination changes are the same in the two records. Hence, we have the intriguing result that the local field changes for two reversals from the same region, but separated in age by 10 Myr, are essentially the same.

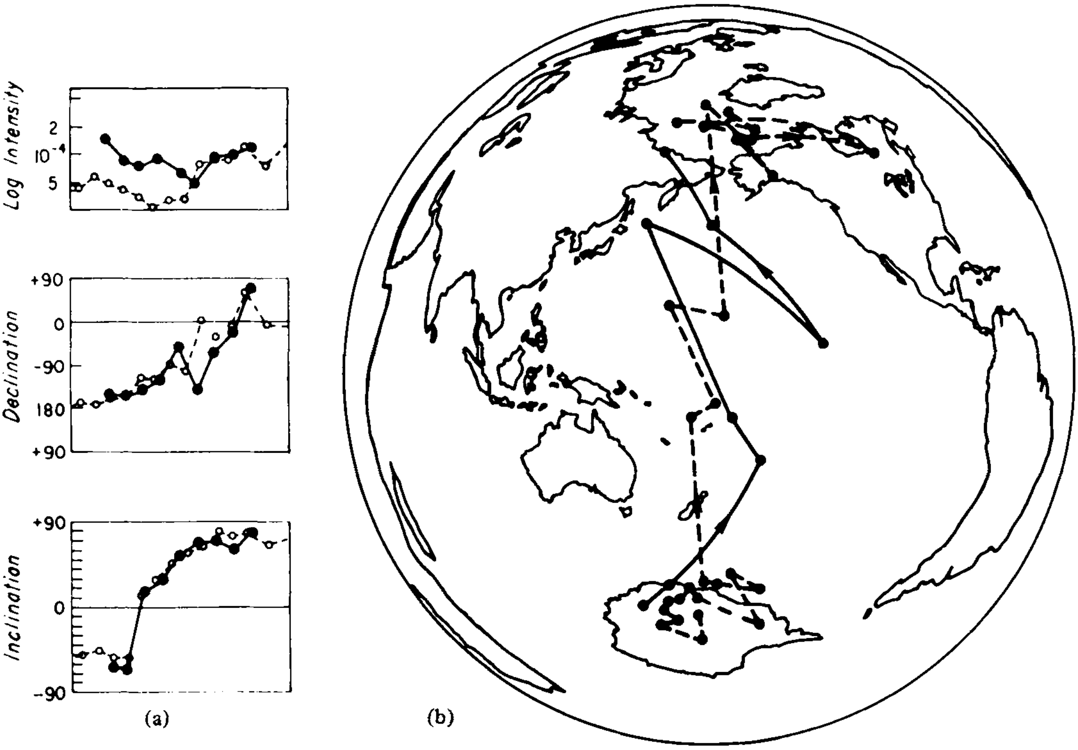

Figure 16. Smoothed record from Laurel Hill (solid line) superposed on Tatoosh record (dashed line), (a) declination, inclination and intensity, (b) VGP paths.

6 The comparison of the Tatoosh and Laurel Hill intrusion record with other late Tertiary and Quaternary reversal records

In comparing the Tatoosh and Laurel Hill records, one is comparing records from similar rocks. However, in comparing records from sediments, lavas and intrusions, it is important to remember the differences between the various recording processes involved. Records from sediments and intrusions are both time-averaged by the recording process. Both types of records should be continuous although a sedimentation hiatus during the reversal can cause an incomplete record in the sediments. Both types of records should however preserve major trends in the VGP paths. In contrast, records from lavas may not show major trends unless they are heavily averaged to eliminate the effect of essentially instantaneous recording at, probably variable, and certainly unknown sampling intervals. The lavas give excellent spot readings of intensity during the reversal. Bearing these factors in mind, we now review the various detailed reversal records which are available.

In addition to the Tatoosh and Laurel Hill records, a number of other records have been reported from western North America. Records have been obtained from sections of lavas in southeast Oregon and northwest Nevada (Watkins 1969; Larson *et al.* 1971; Goldstein, Larson & Strangway 1969) and a record of the last reversal has been obtained from the sediments of Lake Tecopa by Hillhouse & Cox (1976).

The various lava sections may all be recording the same reversal, at approximately 15 Myr, although there is some uncertainty concerning the age of the Poker Jim ridge section described by Goldstein *et al.* (1969). This record will not be discussed further except

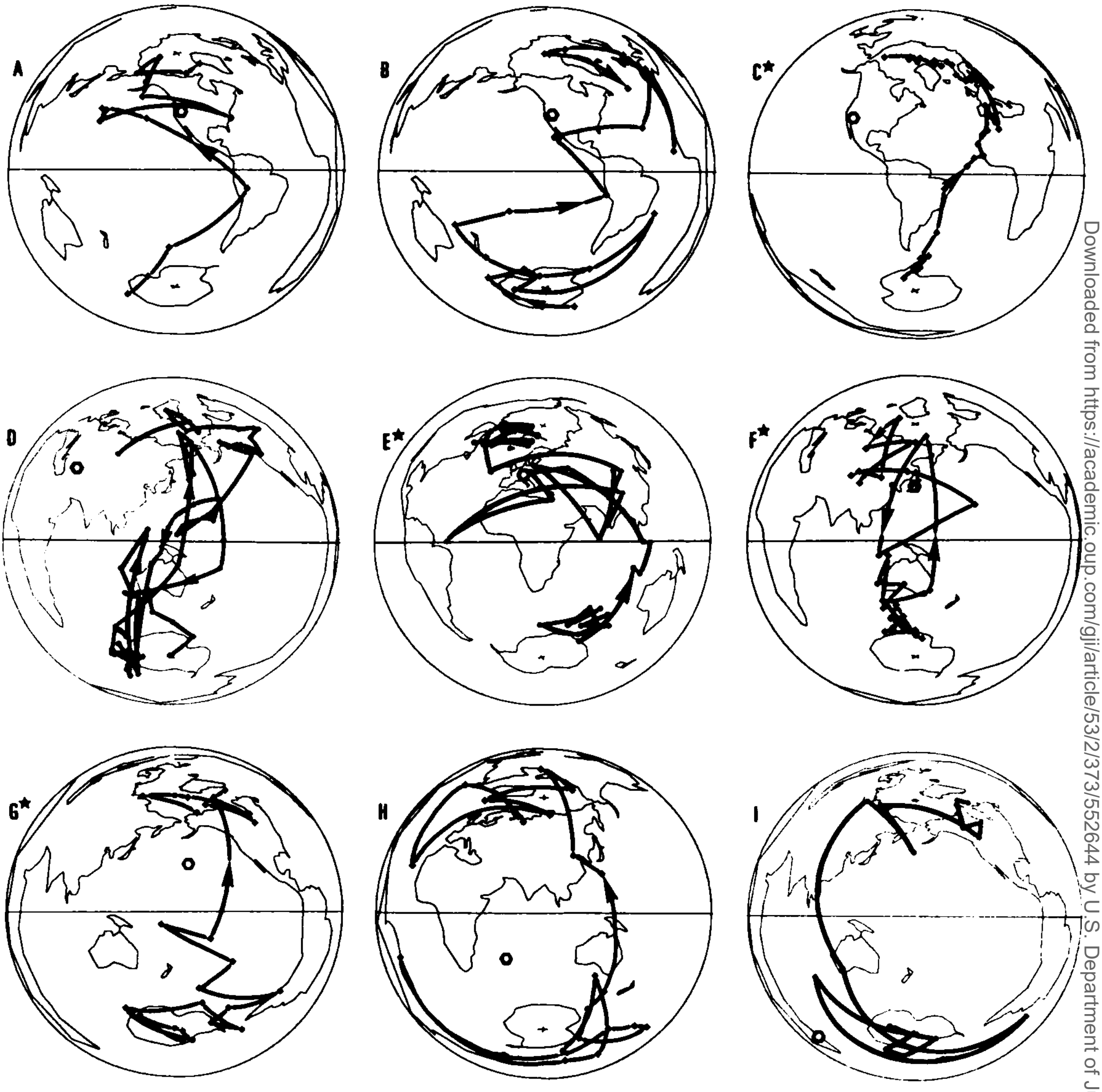

Figure 17. VGP paths of various reversal records: (* = last reversal). (a) Steen's basalt, western USA ($R \rightarrow N$), Watkins *et al.* 1971. (b) Santa Rosa basalts, western USA ($R \rightarrow N$), Larson *et al.* 1971. (c) Lake Tecopa, western USA, Matuyama/Brunhes, Hillhouse & Cox 1976. (d) Turkmenia sediments, Gauss/Matuyama, Burakov *et al.* 1976. (e) Redhill sediments, Czechoslovakia, Matuyama/Brunhes, Koci 1973. (f) Boso peninsula, Japan, Matuyama/Brunhes, Niitsuma 1971. (g) Pacific Ocean core, Matuyama/Brunhes, Kawai *et al.* 1973. (h) Indian Ocean core, Matuyama/Jaramillo, Opdyke *et al.* 1973. (i) Stormberg volcanics, South Africa ($R \rightarrow N$), Van Zijl *et al.* 1962.

to note that it is similar to those from the other two sections. The Steen's Mountain basalts record of Watkins (1969) and the Santa Rosa record of Larson *et al.* (1971) are shown in Fig. 17(a) and (b). Both the records are averaged to permit comparison of the major trends in them. The original Santa Rosa data were averaged to give results for groups of flows. We have averaged the Steen's Mountain data in groups of five. Although the comparison is not perfect, there is considerable similarity between the records. Since these are very likely to be records of the same reversal, they afford some indication of the variation to be expected between different lava records for the same reversal. Such variation is very easily explained by differing extrusive events on a short timescale, with some overall similarity of extrusions at the two sites on the longer timescale. The two records are themselves both similar to the intrusion records; they are somewhat confined in longitude and have paths which traverse the Pacific hemisphere.

The remaining young reversal from the North American landmass is the Lake Tecopa record of the last reversal, documented by Hillhouse & Cox (1976). This is a sedimentary record with individual samples representing a few hundred years, if the reversal is assumed to have taken place over a period of 5000 years. The changes in intensity and direction are related to each other in much the same way as they are in the Tatoosh record. The VGP path (Fig. 17(c)) is, however, quite different from the other paths for North America.

In the comprehensive review of reversal records by Dagley & Lawley (1974), several transitions observed in sections of lavas in Iceland were presented. The authors comment that even though the observation site for all of these paths is the same, the paths vary considerably. However, there does seem to be some tendency for $R \rightarrow N$ transitions to favour paths which traverse the east Pacific or the Americas, while $N \rightarrow R$ paths cross the Euroasian landmass. The authors note that there is a relationship between the latitude of the VGP and the intensity of magnetization, such that low latitude poles correlate with low intensities of the field. Unfortunately these records are defined by small numbers of intermediate samples.

The numerous sedimentary records from the USSR (e.g. Kaporovich *et al.* 1966; Gurary 1973; Burakov *et al.* 1976) reveal first a drop in intensity, then the increase of dispersion of VGP's before the actual reversal in direction begins. Several paths are described and a distinction drawn between simple paths confined in longitude and convoluted paths extending over many degrees of longitude. It is noted that the paths are not randomly distributed. One of the plots for the particularly well documented Matuyama/Gauss transition as observed in Turkmenia is shown in Fig. 17(d).

In Fig. 17(e) the Matuyama/Gauss reversal record obtained by Koci (1973) from a sedimentary section in Czechoslovakia is shown. It is of particular interest because it, like the two intrusion records, appears to reveal a hang up in the VGP path. In this instance, the path starts with motion about a point close to the Antarctic. It then moves relatively rapidly to a northerly latitude comparable to that of the site, where it is centred for some time. From this centre it finally moves to a normal high latitude.

Niitsuma's record of the last reversal, obtained from the sediments of Boso peninsula in Japan is plotted in Fig. 17(f) (Niitsuma 1971). It is one of the best defined of all paths. It is confined in longitude and passes over the site, making it also one of the most clearly near sided VGP paths. No obvious change in intensity was observed. In this record the looping of the VGP paths is much more prominent in the second half of the record than in the first.

Reversal records from oceanic sediments are usually marred by the low sedimentation rates of such samples. However, paths can be traced in some detail in exceptional cores. The Matuyama/Brunhes record (Fig. 17(g)) is due to Kawai *et al.* (1973). The lower Jaramillo $R \rightarrow N$ record (Fig. 17(h)) is from an Indian Ocean core described by Opdyke *et al.* (1973).

There is an almost total absence of reversal records from the southern hemisphere. Fig. 17(i) is the record from the Stormberg volcanics (van Zijl 1962b). Unfortunately the actual transition is not defined by many points. Nevertheless it does seem to represent a near side path for this Triassic $R \rightarrow N$ reversal.

In comparing the various available records a number of common features emerge:

(1) The change in direction of the field is generally accompanied by a decrease in intensity, which is on a demonstrably longer timescale than the change in direction.

(2) After the onset of the intensity decrease and prior to the reversal in direction the dispersion of VGP's increases, with the diameter of loops in the paths increasing.

(3) The reversal in direction is accompanied by varying degrees of convolution of the VGP path, but some confinement in longitude is common.

(4) The best indication of the time taken for the reversal process comes from ocean sediment cores, and indicates that the reversal in direction takes a few thousand years.

In addition to these features which appear to be common to all records of sufficient resolution, there are other features, which although not always seen, should not be totally disregarded. Thus there are the observations by van Zijl *et al.* (1962b) that immediately before the reversal there is an anomalous increase in intensity and that during the transition some high intensities occur. There is the possible preponderance of Pacific paths for northern hemisphere $R \rightarrow N$ transitions, but this effect must be separated from the site control discussed by Hoffman (1977). There is a weak tendency for successive $N \rightarrow R$ and $R \rightarrow N$ reversals to follow a single world-encircling path (e.g. Burakov *et al.* 1976). There is also a weak tendency for the VGP path to hang up at certain latitudes during the reversal and to move rapidly to and from such a centre.

As we noted in the introduction, records of the last reversal are of particular interest because they allow one to compare paths from different sites for a single reversal. The presently available paths are from Lake Tecopa in the western USA (Fig. 17(c)), Czechoslovakia (Fig. 17(e)), Boso peninsula in Japan (Fig. 17(f)), and finally the Pacific (Fig.17(g)). The paths observed by Freed (1977) are similar to those of Lake Tecopa, but are not yet available in published form. It is quite evident that the paths are not all confined to the same longitude. The Czechoslovakian, Japanese and the Pacific Ocean cores are all near sided with the VGP paths passing close to the observation site. This is not so for the Lake Tecopa record from North America. It is curious that the Czechoslovakian path is similar to the Japanese path in the first half of the transition but more like the North American path for the second half. In particular the latter two show considerable drift over longitude lines in the second half of the reversal.

7 Simulation of reversal records

To simulate a reversal record is relatively simple, and yet may be of some help in clarifying our ideas of the nature of the process involved. The dipole field terms are generally reduced to zero and then allowed to grow with the opposite polarity, while some attempt is made to simulate the behaviour of the non-dipole field. Larson *et al.* (1971) carried out such a simulation using a number of subsidiary dipoles placed close to the core–mantle boundary. These were allowed to drift past the site, to simulate the westward drift of secular variation. In this way they were able to generate a sequence of field directions at the site which were similar to those observed in the Santa Rosa lava section.

A simulation of the Tatoosh reversal record has been carried out using the 1965 IGRF in the following way. The axial dipole was initially set in a reversed configuration. Its absolute value was then decreased while the non-dipole terms were allowed to drift westward past the site. The reversal was completed by allowing the axial dipole term to pass through zero and increase in a normal sense. The equatorial dipole terms were not changed throughout the simulation. The simulation reveals (Fig. 18) that westward drift of the present field gives

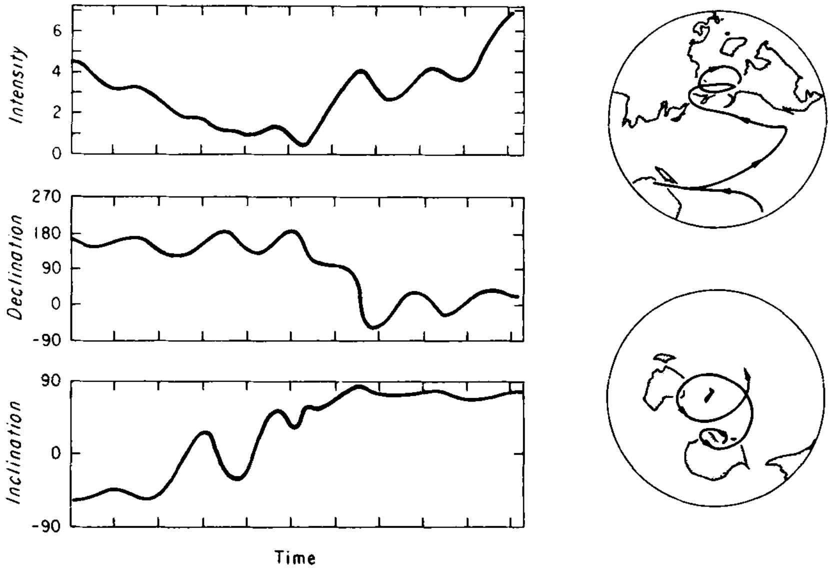

Figure 18. Simulation of reversal.

clockwise loops when the field is normal and anti-clockwise loops when the field is reversed. Without the standing equatorial dipole terms one does not get a VGP path, similar to the observed record.

8 Models of field reversals tested against palaeomagnetic data

In some Nirvanah for experimentalists, observation will always distinguish critically between competing theories. However, neither the theories nor the data of geophysics are often sufficiently precise to permit this happy circumstance. Hence it should not be any surprise that the palaeomagnetic data do not yet critically distinguish between reversal models. Nevertheless, certain models make testable predictions and some can be eliminated.

Probably the simplest model for a reversal, is that the reversal is accomplished by a progressive swing in orientation of the dipole axis with the dipole intensity undiminished in strength. The results from the last reversal indicate that this suggestion is incorrect. A modification of the suggestion is that the dipole is diminished during the reversal, but that the reversal is still accomplished by swinging of the dipole axis and not by the dipole amplitude decreasing through zero. This suggestion is also in conflict with the VGP paths from the last reversal. A variant of this approach by Crane (1974) is that core motions anisotropically shield the dipole field. The shielding is a minimum, when the dipole is axial, and a maximum, when it is oriented equatorially. This suggestion is also inconsistent with the data in that the intensity decrease occurs before a significant change in direction.

The Bullard–Gellman–Lilley dynamo can reverse due to shifts in the field energy carried by different harmonic terms (Lilley 1970). The dipole field is somewhat incidental to the main regenerative process in this model and such a model does not make very precise predictions for reversal behaviour. Nagata (1969) has given a reversal model which is consistent with the reversal frequency data. However, the time constants of the change in direction during the reversal seem short for the decay process he invokes and the nature of the transitional fields is not explained.

A much simplified version of the Parker–Levy model has been analysed by Hoffman (1977) and gives for northern hemisphere sites, VGP paths which pass through the site for $R \rightarrow N$ transitions and pass through the antipodal point to the site for $N \rightarrow R$. The relationship is opposite in the southern hemisphere. The prediction appears to be successful for a number of reversals, but it is not yet adequately tested by the data and it does not account for the gradual change in declination.

Robbins (1976) has described a reversal model, distinguished from the Parker–Levy approach, by the role it ascribes to local changes in the spatial gradients of the rotational velocity of the core. The changes are brought about by the interaction of strong fields and the fluid motion. This model invokes an initial local reversal of the torroidal field, and hence the torroidal field derived non-dipole fields. The switch in the dipole field is then brought about by the α process. It, like the Parker–Levy model, predicts reversal times short compared with the core diffusion time. Transitional paths dominated by quadrupolar or octupolar fields appear likely. The localization of the initial torroidal field reversal could however give non-axisymmetric fields and account for the VGP paths observed.

In contrast to the various $\alpha\omega$ dynamos which have been used to explain the solar and geomagnetic dynamos (e.g. Babcock 1961; Leighton 1964; Krause & Rädler 1971; Bullard 1955; Lilley 1970; Ribbins 1976; Parker 1955; Levy 1971, 1972), there are a number of dynamos in which field generation is by the α process alone and does not involve a torroidal field generated by the ω process. Such dynamos are attractive because they recognize that the convection and hence the rotational velocity gradients in the Earth's core are likely to be much smaller than those in the solar field generating regions. In such α^2 dynamos it is convenient to consider the α effect in terms of current produced parallel to the field lines as was demonstrated by Steenbeck *et al.* (1967). One such dynamo is the DC turbulent dynamo (Steenbeck & Krause 1969). It remains to be seen whether the presence of such turbulence in the core can be demonstrated and whether large scale field generation follows. Yet the dynamo has the interesting feature that the eigenvalues for dipole and quadrupole fields are similar. Hence, although this dynamo is described as a DC dynamo, it appears to have ingredients which might readily give an infrequent reversal with transitional quadrupole fields.

Fig. 19 illustrates a possible mode of reversal which is consistent with the observed records. The initial dipole field decreases by about one order of magnitude, so that locally non-dipole field anomalies may be stronger than the remaining dipole field. During such a time a non-dipole anomaly of opposite sense develops in the southern high latitude region of the core. The strong regenerative processes in this region ensure that it overcomes the remaining weak dipole field and a torroidal field of the opposite sense is generated (Fig. 19(b)). The field then attains a quadrupole configuration as the stronger normal field diffuses northward and switches the sign of the field in the southern hemisphere (Fig. 19(c)). The field may then stabilize in this configuration temporarily. Alternatively, northward diffusion of the new southern hemisphere field may sweep through low latitudes where the regenerative process is weakest (Fig. 19(d)). This process eventually gives a normal configuration for the dipole field. This mechanism is admittedly highly speculative and not developed quantitatively but it does have a number of features which are consistent with observations.

(1) A reversal should be a rare event because it requires a very substantial reduction in strength of the dipole field coupled with the fortuitous development of non-dipole features of appropriate sign. In this sense the model is similar to the Cox (1969) suggestion and hence is also compatible with the distribution function for reversal intervals.

(2) Like almost all models it predicts an intensity change over a longer time period than the change in direction.

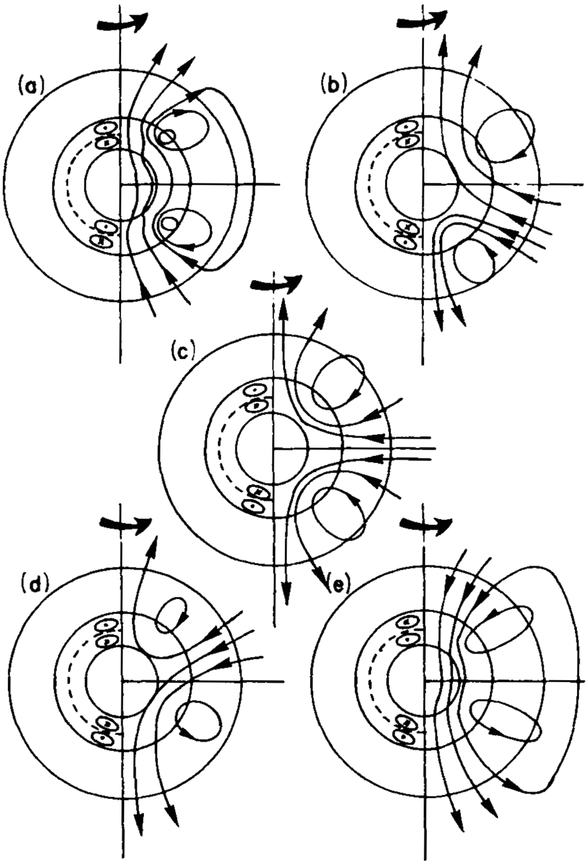

Figure 19. Reversal geometry for quadrupole transition field. On the left of each figure, lines of equal torroidal field (X out, · in). On the right poloidal field line.

(3) The model predicts confined VGP paths because of the dominance of axisymmetric quadrupolar fields during the transition. Whether the path is antipodal or passes through the site depends upon whether the northern or southern hemisphere field switches first to give the quadrupole field, and whether the reversal is $N \rightarrow R$ or $R \rightarrow N$. An $R \rightarrow N$ reversal with the southern hemisphere switching first gives a site path as illustrated in Fig. 19.

(4) The reversal process may be somewhat asymmetric depending upon the site latitude and whether the site is in the hemisphere which switches before or after the quadrupole field state. If the site is in the hemisphere which switches after the quadrupole state, there will be an initially rapid transition to low latitude and then a slower recovery to higher inclination as may be seen in the Tecopa $R \rightarrow N$ record.

(5) One type of excursion of the field could be caused by recovery of the initial polarity from the quadrupole state.

The model fails to account for the non-zero declination of the various records. This requires the presence of some non-axisymmetric field component. More detailed tests of the model await additional reversal records.

The reversal of the DC dynamo described above demonstrates that relatively simple reversal geometries can be devised for such dynamos. Indeed one suspects that other dynamos such as the $\alpha\omega$ models and those of Braginskii (1964) and Busse (1976) could also give similar simple geometries. Quadrupolar fields during transitions have been previously suggested by P. H. Roberts (private communication) and are prominent during the solar field reversal (e.g. Gubbins 1974). It is our interpretation that axisymmetric fields, probably quadrupolar, may dominate the geomagnetic reversal process. Moreover the records from the last reversal suggest that if so, the southern hemisphere switched first to give the quadrupolar field. However, to explain the observed paths some non-axisymmetric component of the field is required. Such a distinction between persistence of non-zonal fields in the presence of switching to zonal fields is consistent with the analysis of Yukutake (1977).

Whether the proposed dominance of axisymmetric fields during the reversal necessitates some particular dynamo is not clear. It is entirely possible that either α^2 or $\alpha\omega$ dynamos can give axisymmetric transitional fields. Nevertheless a clear-cut demonstration of the nature of the transitional fields would be a very useful contribution for palaeomagnetism to make to dynamo theory and it appears to be almost within reach of present technique. Such studies are most easily accomplished for the last reversal. They should also include a careful search for precursory oscillations in the intensity of the field, prior to the reversal to see if the field gives evidence of changing state at that time.

Acknowledgments

This work was supported by NSF grants 835 and 13135. We thank Dr A. Corcoran of the Oregon Geological Survey for his help in the initial fieldwork and Dr N. Bishop for making the arrangements for the work in Mount Rainier National Park. We acknowledge the help of the members of the Rock Magnetism groups at UC Santa Barbara and at the University of Pittsburgh, and in particular John De Journett who made many of the measurements. We are also grateful to Professor T. Nagata for his continued interest and encouragement in this work over the years, and Dr K. Hoffman for many stimulating discussions in the summer of 1976 and subsequently, in which he developed our appreciation of the possible importance of the site dependence of the VGP paths.

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